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SOLAR ENERGY SYSTEM PERFORMANCE EVALUATION - SEASONAL REPORT FOR IBM SYSTEM 4 AT CLINTON, MISSISSIPPI

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For the U. S. Department of Energy

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Solar Energy

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1. FOREWORD

<u>The Solar Energy System Performance Evaluation</u> - <u>Seasonal Report</u> has been developed for the George C. Marshall Space Flight Center as a part of the Solar Heating and Cooling Development Program funded by the Department of Energy. The analysis contained in this document describes the technical performance of an Operational Test Site (OTS) functioning throughout a specified period of time which is typically one season. The objective of the analysis is to report the long-term performance of the installed system and to make technical contributions to the definition of techniques and requirements for solar energy system design.

The contents of this document have been divided into the following topics of discussion:

- System Description
- Performance Assessment
- Operating Energy
- Energy Savings
- Maintenance
- Summary and Conclusions

Data used for the seasonal analyses of the Operational Test Site described in this document have been collected, processed and maintained under the OTS Development Program and have provided the major inputs used to perform the long-term technical assessment. The data have been archived by the Marshall Space Flight Center for the Department of Energy.

The Seasonal Report document in conjunction with the Final Report for each Operational Test Site in the Development Program culminates the technical activities which began with the site selection and instrumentation system design in April 1976. The Final Report emphasizes the economic analysis of solar systems performance and features payback performance based on life cycle costs for the same solar system in various geographic regions. The other documents specifically related to this system are References [1] through [3].*

*Numbers in brackets designate references found in Section 8.

2. SYSTEM DESCRIPTION

The IBM System 4 Solar Energy System was designed to provide space heating and domestic hot water preheating for a single-family residence located within the United States. Areas of application include all regions of the U.S. except the extreme north, and regions with low heating degree days, such as southern California and Florida. The solar system is a prepackaged unit called the Remote Solar Assembly which is documented for gross collector areas of 191, 259 and 327 square feet. The system fabricated for performance evaluation is Remote Solar Assembly, 7934930-2 as documented in Reference [3]. It is integrated into the heating and domestic hot water systems in the dormitory at the Mississippi Power and Light training center in Clinton, Mississippi. Solar energy collection is accomplished with Solaron 2001 series flat-plate collectors using air as the transport fluid. The collector array has a gross collector area of 259 square feet and faces due south inclined at a tilt angle of 45 degrees from the horizontal. Air is circulated by two blowers. One blower circulates air from the collector array to storage. The other blower circulates air from the collector array or the rock storage bed to the load (building). Air passes through the air to water heat exchanger which is duct mounted at the hot air inlet of the rock storage bed. Solar heated water in the heat exchanger circulates by thermosyphoning to a 52 gallon preheat tank. Supply water for two 30 gallon hot water tanks is drawn from the preheat tank. Solar energy is stored in a rock storage bed containing 11,100 pounds of rock. Auxiliary energy for the hot water and space heating subsystems is provided by a 4kW electric heater in each hot water tank and a 20 kW electric duct mounted strip heater respectively. The system, shown schematically in Figure 2-1, has three basic modes of operation. The sensor designations in Figure 2-1 are in accordance with NBSIR-76-1137 [4]. The measurement symbol prefixes; W, T, EP and I represent respectively: flow rate, temperature, electric power, and insolation. The IBM System 4 installation at Clinton Mississippi is illustrated in Figure 2-2.

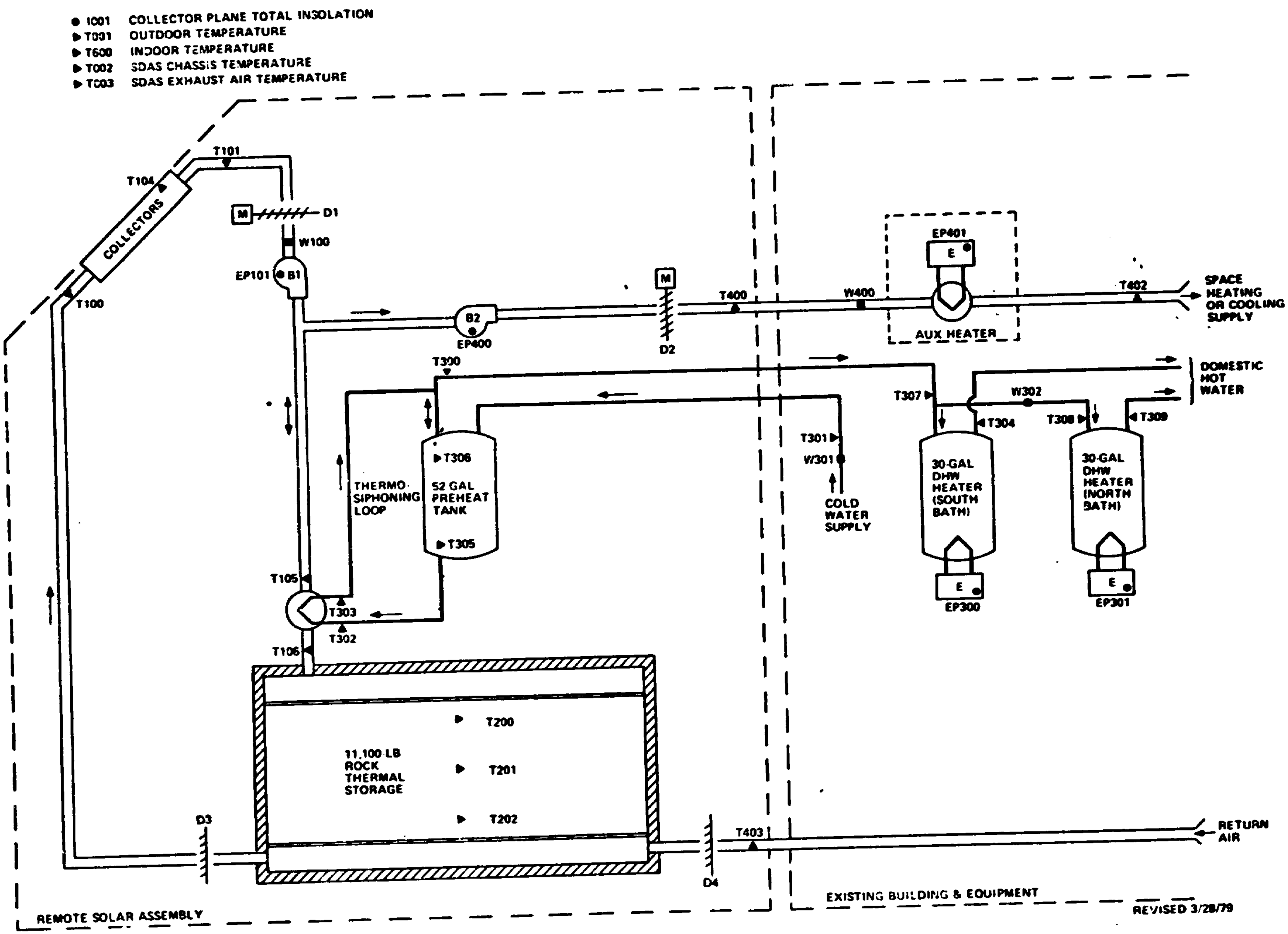


Figure 2-1 IBM System 4 Solar Energy System Schematic

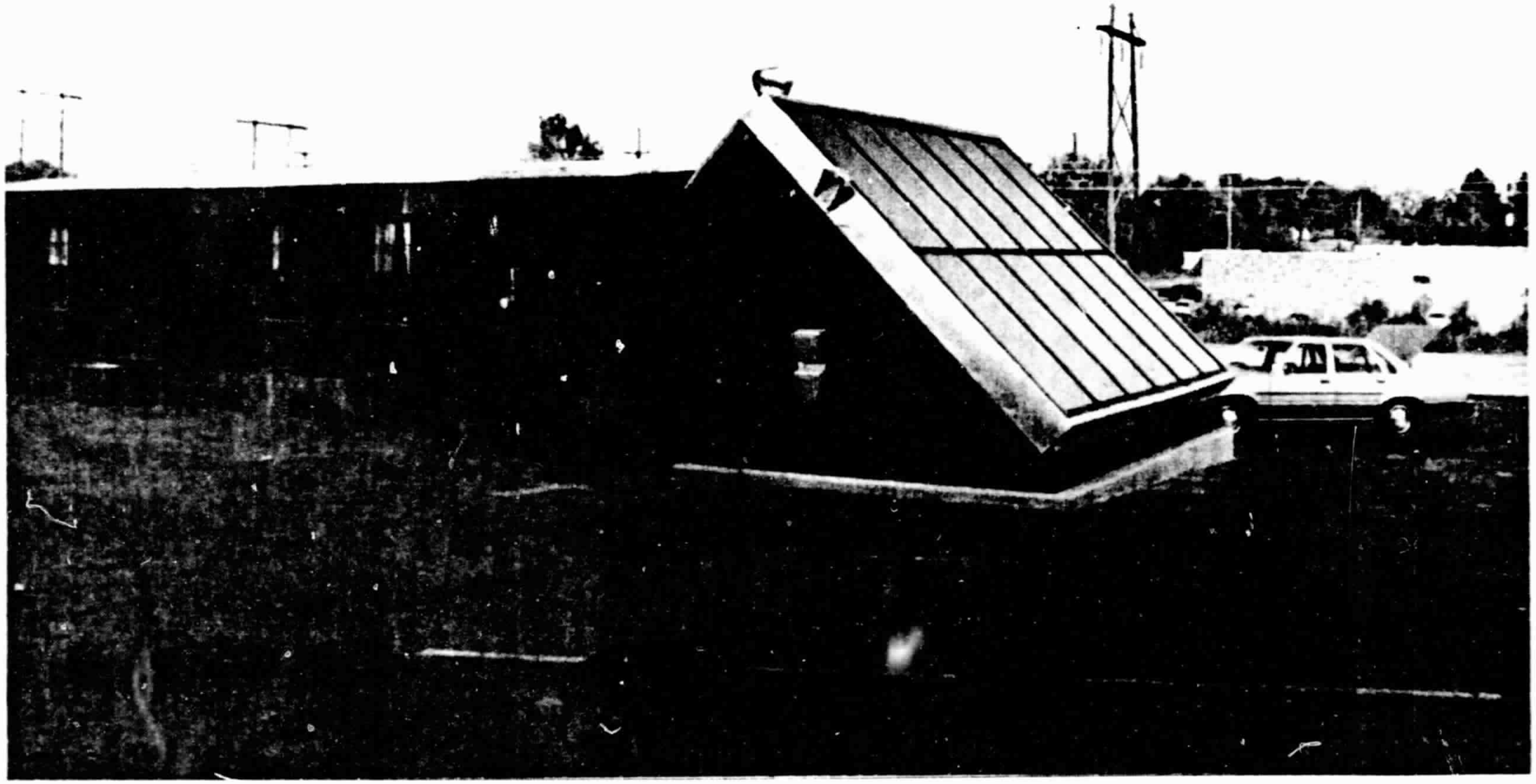


Figure 2-2 IBM System 4 Installation at Clinton, Mississippi

Mode 1 - Collector-to-Storage: The system operates in this mode whenever the space heating demands have been satisfied and additional solar energy is available for heating. Solar heated air from the collectors is passed through the duct mounted air to water heat exchanger on its way to the rock storage bed. Solar energy is therefore stored in the preheat tank as well as in the rock storage bed. In this mode the collector blower is operating and the space heating blower is off.

Normal Mode - The Normal Mode is selected by manually positioning the summer mode switch to "off." The collector blower and its control damper operation are automatically initiated in this mode by a differential temperature controller when the temperature difference between the outlet of the collector and bottom rock storage exceeds 40°F. Collector blower operation continues in this mode until the temperature difference decreases to less than 25°F or until the top of rock storage or preheat tank temperatures exceed 200°F or 170°F, respectively.

Summer Mode - The Summer Mode is selected by manually positioning the summer mode switch to "on." The collector blower and its control damper are automatically initiated in this mode by two differential temperature controllers when either (1) the temperature difference between the outlet of the collector and bottom of rock storage exceeds 40°F, or (2) the temperature difference between the bottom of rock storage and the bottom of the preheat tank exceeds 40°F. Collector blower operation continues until the temperature difference which inititated the blower operation is decreased to less than 25°F or until the top of rock storage or preheat tank temperatures exceed 200°F or 170°F, respectively.

Mode 2 - Collector-to-Load: The system operates in this mode whenever solar energy is available at the collectors and there is a demand for space heating. Both the collector blower and the space heating blower operate in this mode. Collector blower operation is initiated as described in Mode 1. The space heating blower and its associated control damper operation are initiated by the first stage contacts of the site dwelling thermostat.

Mode 3 - Storage-to-Load: The system operates in this mode whenever there is a demand for space heat. The space heating blower and its control damper operation are initiated by the first stage contacts of the site dwelling thermostat.

NOTE 1: Auxiliary heat is utilized in Mode 2 and 3 when the site thermostat second stage calls for heat or when the site thermostat first stage calls for heat when the rock storage temperature is below 90°F.

NOTE 2: Domestic water preheat occurs in all three modes whenever the air temperature across the heat exchanger is higher than the city water supply temperature.

2.1 Typical System Operation

Curves depicting typical normal mode system operation on a cool bright day (March 2, 1980) are presented in Figure 2.1-1. Figure 2.1-1(a) shows insolation on the collector array and the period when the collector blower is operating (shaded area). On this particular day the collector blower did not appear to cycle at start-up (0834 hours) or at shut-down (1612 hours); at least cycling was not discernable within the 5.33 minute resolution of the data collection system.

Figure 2.1-1(b) shows typical collector array temperatures during the day. The low limit temperature readout for the three temperature measurements is approximately 32°F. Since the collector array temperatures in the absence of solar radiation approach the temperature of the environment, which was in the low 20°F range in the early morning and late evening, the actual collector temperatures were not measurable at that time. As the sun started to rise, at approximately 0652 hours the collector array started to warm up, but not until 0719 hours did the absorber temperature (T104) rise above the 32°F low limit. The collector blower started at 0827 hours when the absorber temperature (T104) was 137°F. The array control sensor is located in one of the two outlet collector plenums. Its temperature is not monitored; however, it can be assumed to have been about 105°F because system control requires a 40°F temperature differential between bottom of storage and collector plenum.

During the operational period of the collector blower the absorber temperature (T104) and array exit temperature (T101) generally lagged the insolation level with T101 showing the greater lag. Collector inlet temperature remained fairly constant at 60°F to 70°F. This was due to the fact that the bottom of storage did not rise appreciably above the return air temperature from the dwelling.

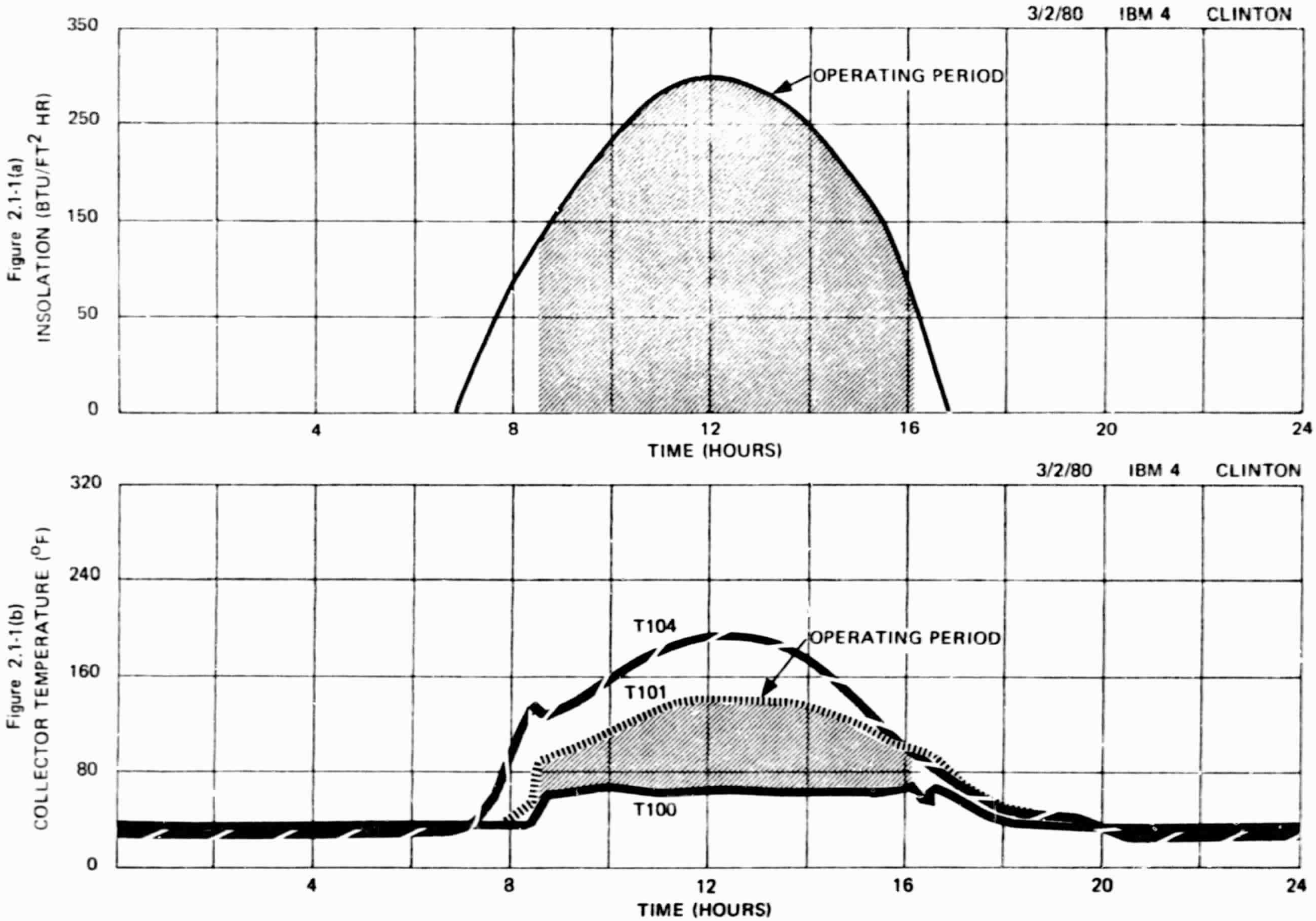


Figure 2.1-1 Typical System Operating Parameters for Collector Array in Normal Mode of Operation

Figure 2.1-2(a) shows the temperature profile of the three temperature measurements in the rock storage bed. Measurement T200 is at the top center of the bed four inches down from the top surface of the pebbles. Measurement T201 is at the geometric center of the bed. Measurement T202 is at the bottom center of the bed four inches up into the pebbles from the surface of the metal grating which supports the pebbles. During the early morning hours the storage bed is depleted of energy and the three storage temperatures are between 53°F and 65°F, approximately the same temperature as the return air temperature from the dwelling. Since return air always passes through storage, even when storage is depleted, there are periods of time when return air maintains storage at essentially return air temperature by adding heat to storage to make up for heat being lost to the environment (essentially outdoor conditions). This condition existed during the morning until 0900 hours and late in the evening after 2100 hours.

Figure 2.1-2(b) shows the temperature profile of the two temperature measurements in the preheat tank and the two water temperature measurements at the inlet and outlet of the air-to-water heat exchanger. There was no hot water consumed on this day. The temperature difference between the top of the preheat tank (T306) and bottom of preheat tank (T305) varied from 27°F during the very early morning to 10.4°F at 1513 hours. The temperature of the water decreases during the early morning hours as heat is lost from the preheat tank to the environment until approximately 1130 hours when thermosyphoning action begins, i.e., water begins to flow from heat exchanger to preheat tank. The temperature of the tank continued to rise from 1130 to 1514 hours. Prior to 1020 hours, the outlet from heat exchanger (T303) is higher in temperature than the inlet to heat exchanger (T302). Between 1020 hours and 1130 hours the temperature relationship reverses and the inlet temperature becomes higher than the outlet temperature. The temperature reversal is the result of the heat exchanger warming up. The inlet to preheat tank, measured by T302, is the shorter distance from the heat exchanger and warms up faster. As the water temperature within the heat exchanger exceeds the temperature at the top of the preheat tank, thermosyphoning flow begins at 1130 hours. As flow begins the inlet to heat exchanger, T302, drops rapidly as water from the bottom of preheat tank flows to the heat exchanger. Flow from the heat exchanger continues until the water temperature in the heat

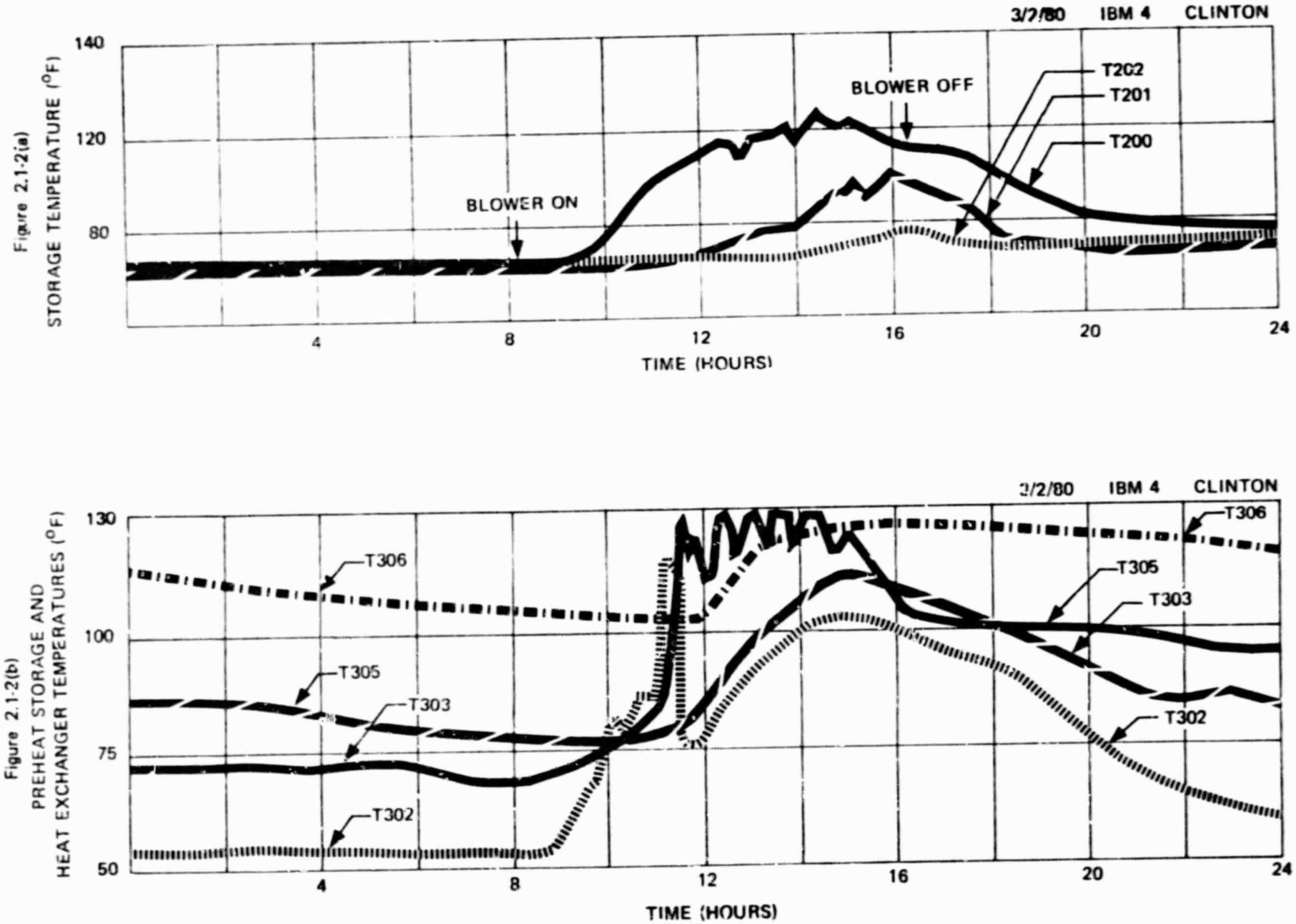


Figure 2.1-2 Typical System Operating Parameters for Rock Storage, Preheat Tank and Heat Exchanger in Normal Mode of Operation

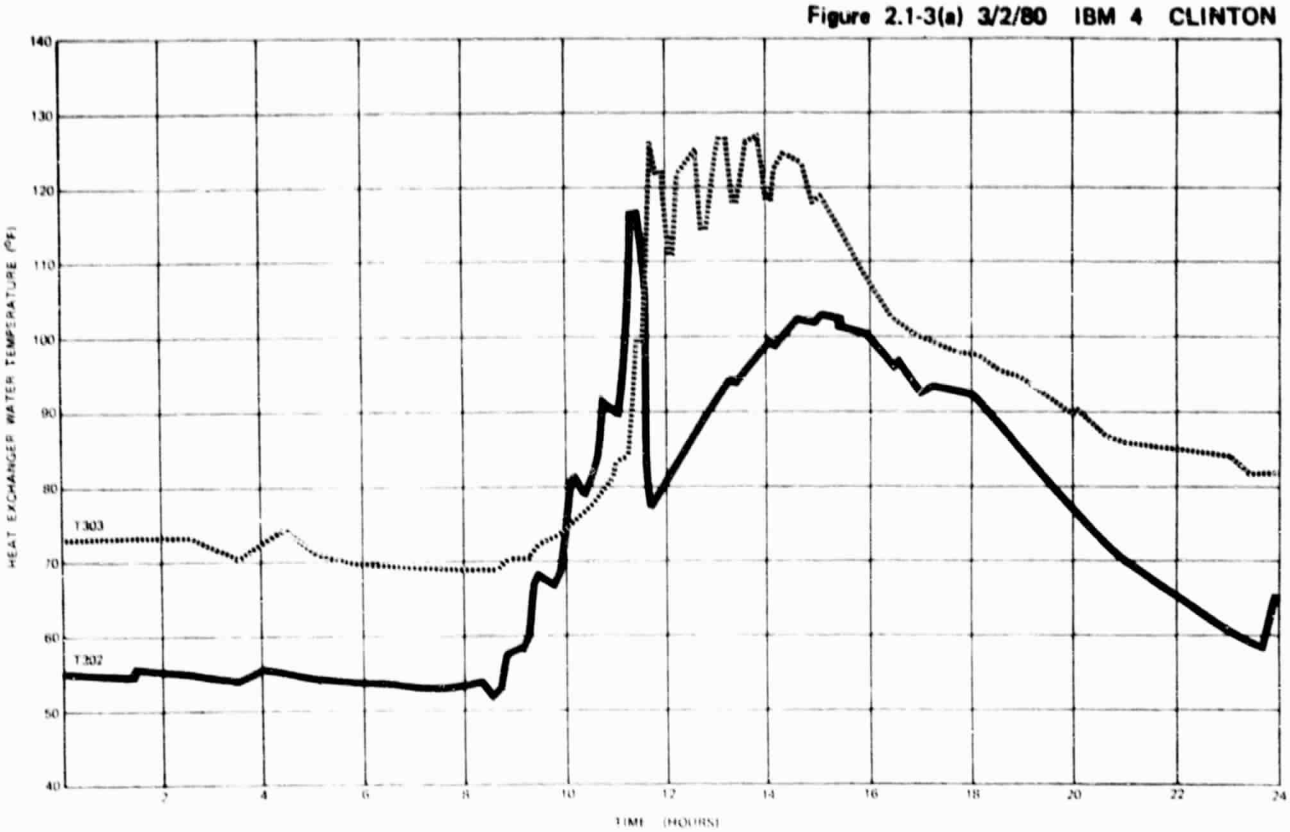
exchanger decreases below the water temperature at the top of the preheat tank at approximately 1514 hours. It should be understood that the measurements at the inlet (T302) and outlet (T303) temperature measurements do not measure the exact temperature within the heat exchanger either before or after water flow begins. Also the temperature measurements at the top (T306) and bottom (T305) of the preheat tank do not measure the top-most or bottom-most location within the tank. Therefore the average of the heat exchanger inlet and outlet temperatures (T306 + T305)/2 is not necessarily equal the temperature at the top of the tank when water flow begins or ceases.

Figure 2.1-3(a) shows heat exchanger water inlet temperature (T302) and water outlet temperature (T303) for the same day of operation as Figure 2.1-2(b). Figure 2.1-3(b) shows the air temperature at the top (T105) and bottom (T106) of the heat exchanger.

As thermosyphoning action begins the air inlet to the heat exchanger (T105) is 133°F and the air temperature difference across the heat exchanger is less than 1°F. A maximum air temperature difference across the heat exchanger of 15°F occurred at 1102 hours. The inlet air temperature (T105) and water outlet temperature (T303) are both 116°F when thermosyphoning flow ceases at 1514 hours.

Figures 2.1-4 and 5 shows typical summer mode system operation on a hot bright day, June 20, 1979. Figure 2.1-4 shows insolation on the collector array and the period when the collector blower is operating (shaded area). On this particular day the collector blower did not cycle at start-up (0904 hours); however, it did cycle twice at shut-down. The first shut-down was at 1446 hours the second at 1507 hours and the final shut-down at 1528 hours.

Figure 2.1-5 shows typical collector array temperatures during one day of operation. The collector blower operated nine times during the early evening from zero hours until 600 hours to transfer heat from rock storage to the preheat tank. The collector blower operated again for the



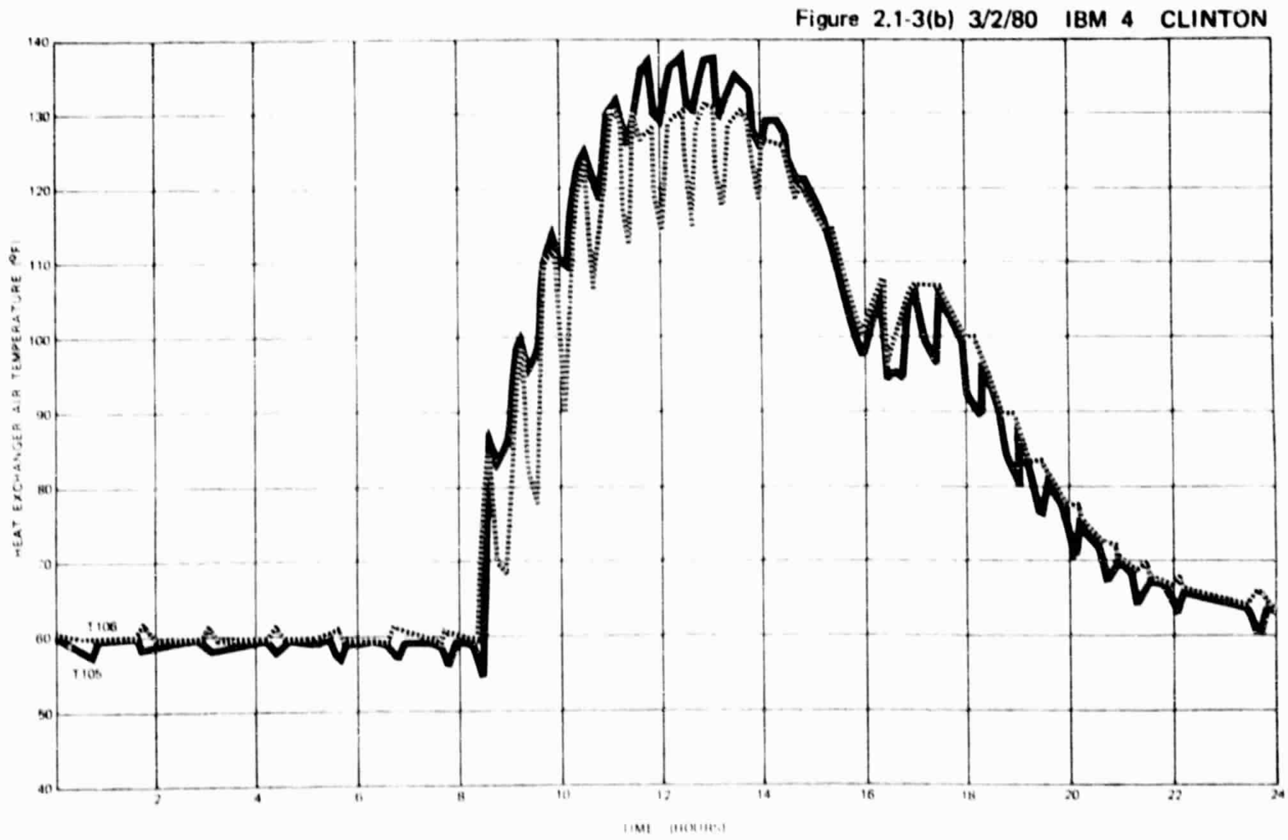


Figure 2.1-3 Typical Operating Parameters for Air to Water Heat Exchanger in Normal Mode of Operation

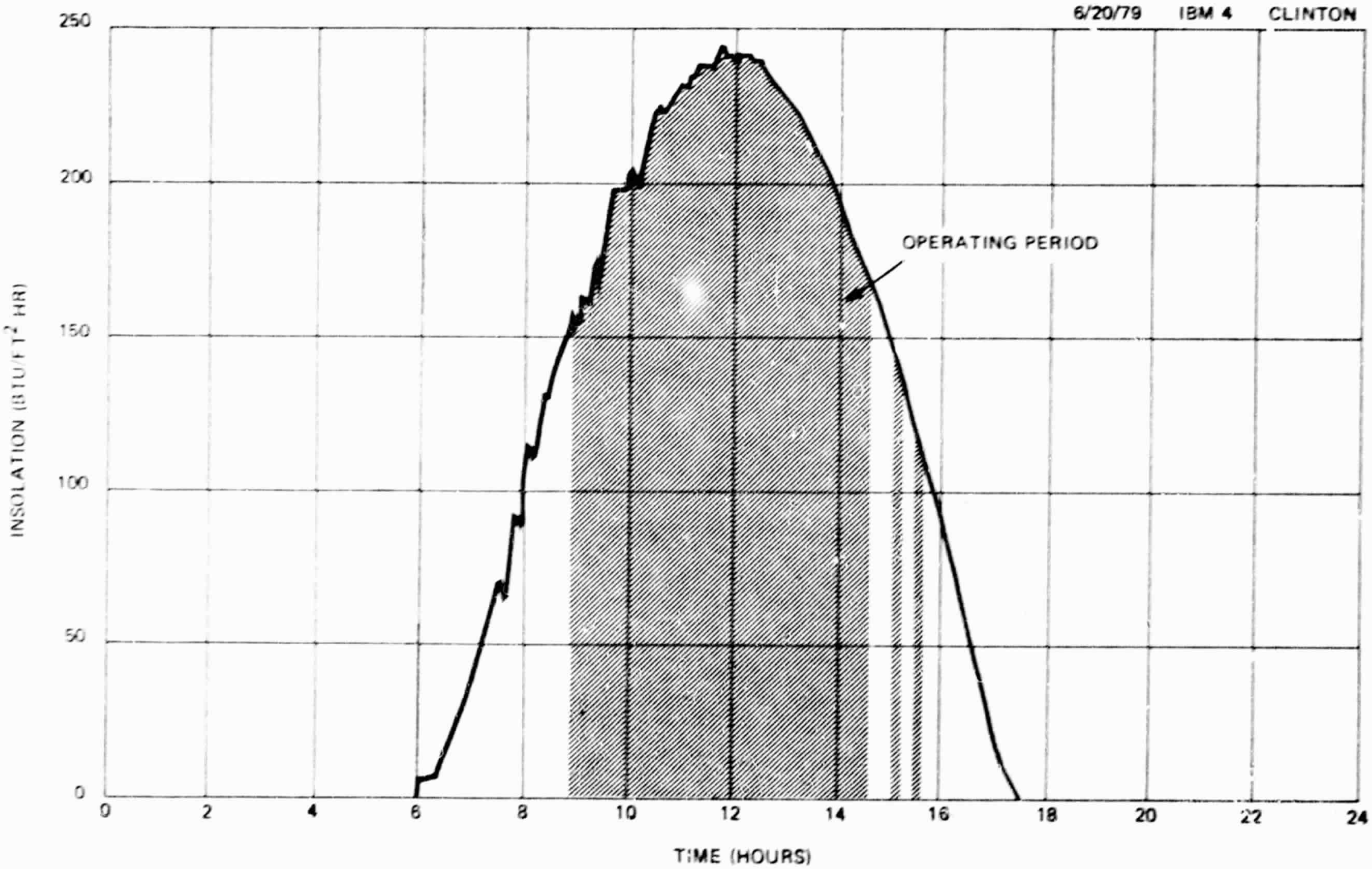


Figure 2.1-4 Insolation on Collector Array

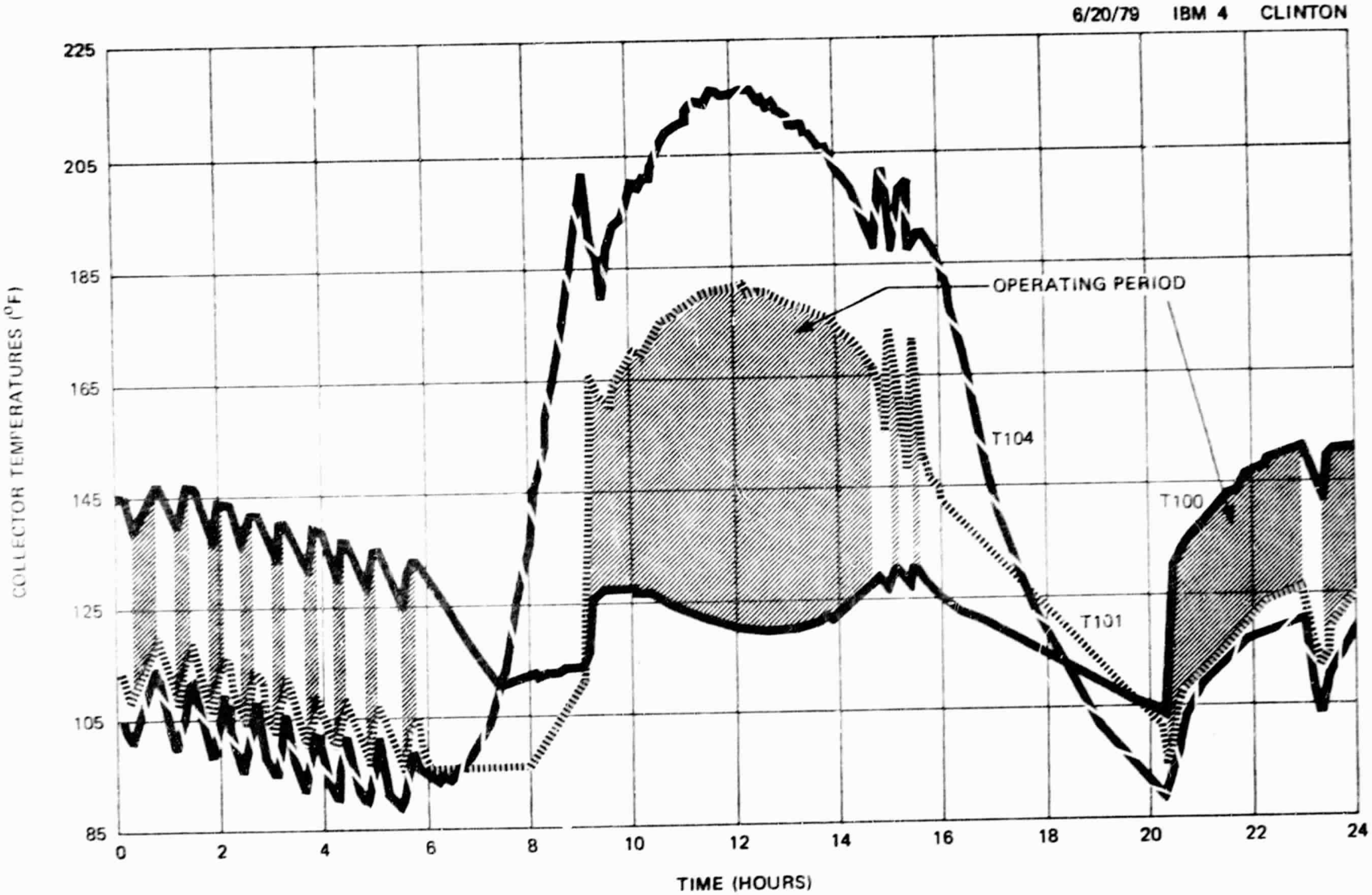


Figure 2.1-5 Typical Operating Parameters for Collector Array in Summer Mode of Operation

same purpose in the late evening from 2027 hours until 2307 hours and from 2334 hours until 2400 hours. The temperature difference from inlet (T100) to outlet (T101) of the collector during the night-time operation was relatively constant at 30°F. The temperature difference during the day light hour reached a maximum of 62°F shortly after 1200 hours. The collector blower started in the morning at 0904 hours when the absorber temperature (T104) was 202°F. The bottom of storage (T202) at that time was 108°F. Since the collector blower is initiated when the temperature difference between these two points is 40°F, either T104, T202 or both measurements were considerably different than the locations of the control sensors which are at the bottom of storage and top collector array plenum. A much higher temperature difference also occurred between these two points at collector blower shut-down than the 25°F required by the controller sensors. The saw tooth appearance of the temperature profiles of the collector array temperatures indicates a rapid temperature drop and increase when the blower cycles.

Figure 2.1-6 shows the temperature profile of the three measurements in the rock storage bed on June 20. During the early and late evening hours energy is being rejected through the collectors and storage temperatures were dropping. At that time the top of storage (T200) is colder than the bottom (T202). During the day-light hours the temperature stratification reverses and the top of storage becomes hotter than the bottom.

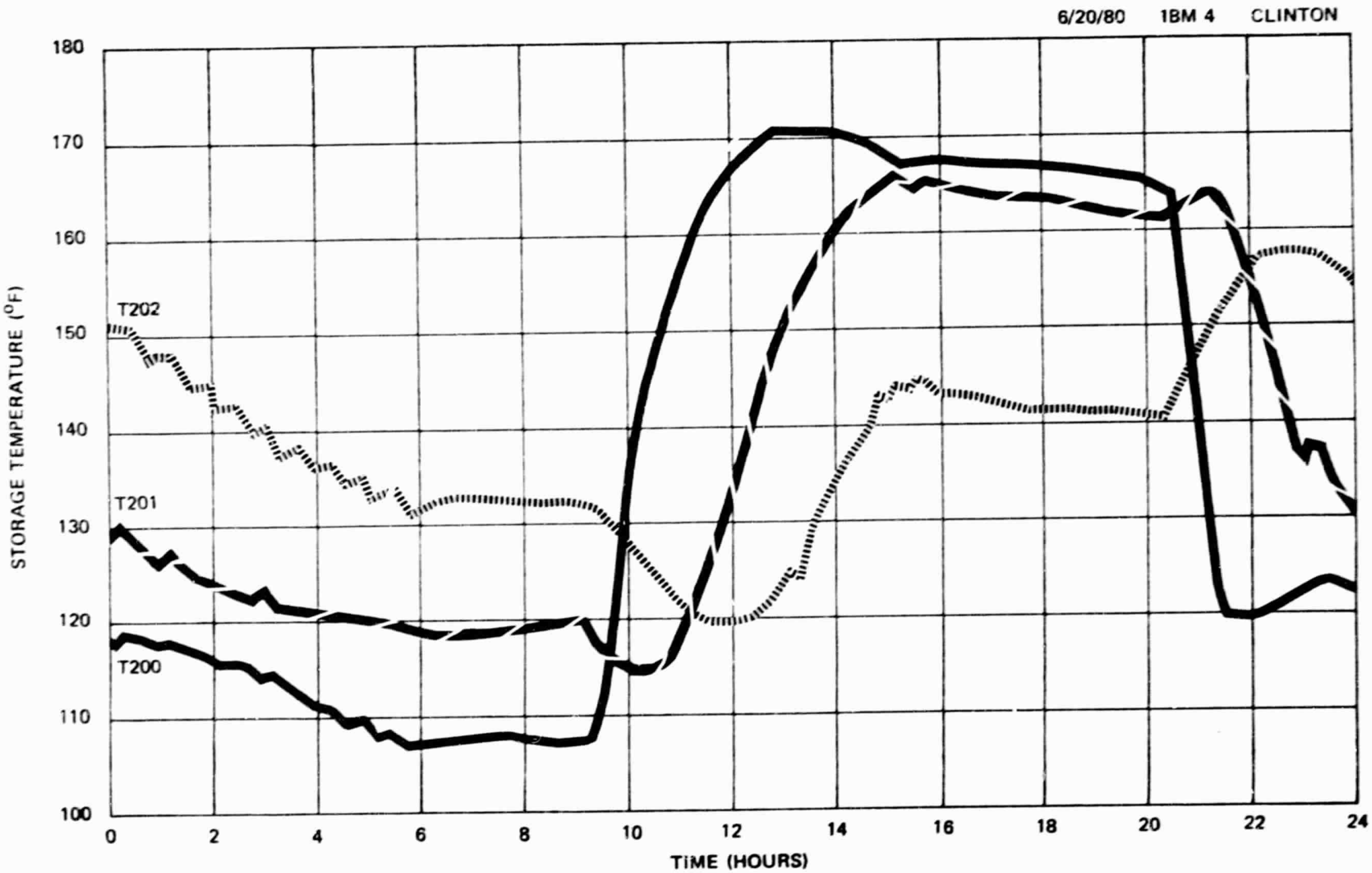


Figure 2.1-6 Typical Operating Parameters for Storage Bed in Summer Mode of Operation

2.2 System Operating Sequence

Figure 2.2-1 presents bar charts showing typical normal mode system operating sequences for March 2, 1980. This data correlates with curves presented in Figures 2.1-1, 2.1-2, and 2.1-3 and provides some additional insight into those curves.

On this particular day the collector blower operated continuously from 0822 hours until 1607 hours. Solar energy from the collector array was either delivered to the load or storage. During the early morning and late evening there was heavy utilization of auxiliary space heat. After the collector array became operational, auxiliary space heat was still required until 1130 hours; however, no auxiliary energy was then required until 1831 hours. It should be understood that the bar chart indicates the period of time that solar energy or auxiliary energy was operational; however, the quantity of each energy transfer is not represented.

No domestic hot water was drawn on this day. Therefore, no solar energy collected in the preheat tank was delivered to the hot water tanks. The auxiliary domestic hot water energy utilized was required to supply the energy lost to the environment and maintain hot water tanks 1 and 2 at the set point temperatures.

March 2, 1980

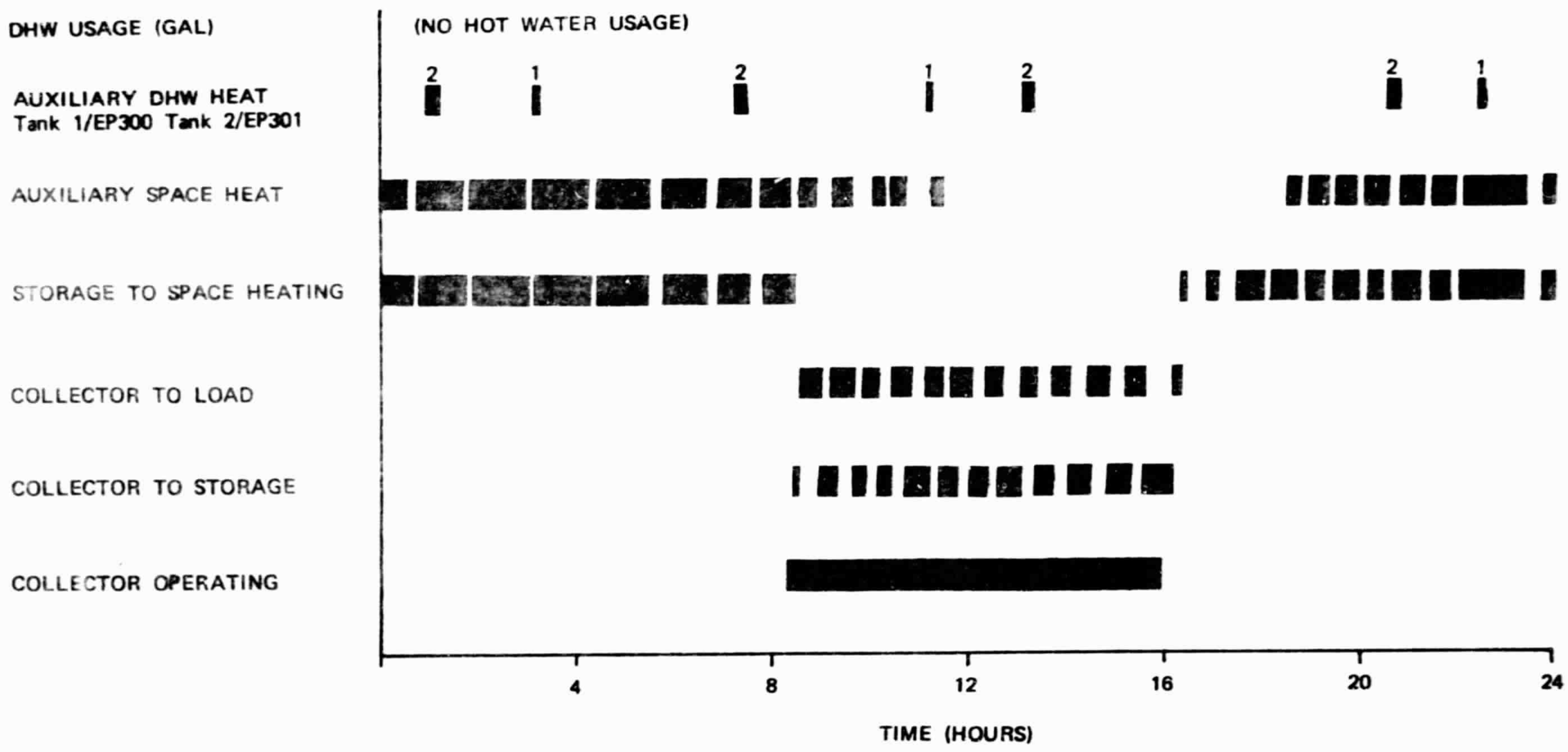


Figure 2.2-1 Typical System Operating Sequence

3. PERFORMANCE ASSESSMENT

The performance of the IBM System 4 Solar Energy System has been evaluated for a one year time period from two perspectives. The first was the overall system view in which the performance values of system solar fraction and net energy savings were evaluated against the prevailing and long-term average climatic conditions and system loads. The second view presents a more in-depth look at the performance of the individual subsystems. Details relating to the performance of the system are presented first in Section 3.1 followed by the subsystem assessment in Section 3.2.

For the purposes of this Solar Energy System Performance Evaluation, monthly performance data were regenerated to reflect refinements and improvements in the system performance equations that were incorporated as the analysis period progressed. These modifications resulted in changes in the numerical values of some of the performance factors. However, the basic trends have not been affected.

Before beginning the discussion of actual solar energy system performance, some highlights and pertinent information relating to site history are presented in the following paragraphs.

The IBM System 4 Solar Energy System was initially brought on line in October, 1978. At that time all known system problems were addressed and corrected where possible. After the system became operational, a period of data monitoring was initiated to verify that solar system and monitoring instrumentation were functioning properly.

During the system check-out phase, a temperature range change was made to measurement T300, T302, T303, T306, T307 and T308 because measurements were near or exceeding 160°F full scale reading. The upper limit of these measurements was changed from 160°F to 230°F in October 1978.

In early November, 1978, it was observed that the indoor building temperature was dropping as much as 7°F below the set point during periods of heavy space heat demand. This problem was caused by the increased electrical current flowing through the control thermostat when the strip heaters were being energized by the thermostat second stage contacts. This increased load on the thermostat caused excessive thermostat anticipator action. The problem was eliminated by adding a relay to the system control circuit so that the same current would be flowing through the thermostat when either first or second stage control was required.

The performance of the domestic hot water flowmeter W301 and W302 were difficult to assess because there were frequent periods of no occupancy. W302 was initially erratic and finally failed in October, 1978. It was replaced on November 6, 1978.

The domestic hot water supply line froze several times in January, 1980, because it was installed above ground level. This problem was corrected by wrapping the lines with a heater tape and insulation. The installation of the heater tape did affect the supply water temperature during periods of low hot water flow, however, during periods of reasonable flow the true ground water temperature was measured.

A fogging of the Solaron 2001 Series collector glazings was encountered with several of the collectors in the array. The fogging was condensed water particles on the inside surface of the glazing during the early morning. This condition was presumed to occur because of faulty sealing of the glazing assembly. As solar radiation began during the day this condensation quickly evaporated and was no longer visible. During February, 1979, three glazing assemblies were replaced on three of the collectors which exhibited the most condensation.

In May, 1979, the bypass valve around the preheat tank was found open. It was not known when this valve had been inadvertently left open, but it was suspected that the valve had been left open on December 12, 1978, when a small water leak in a pipe union at the preheat tank was repaired. The open bypass valve caused supply water to the hot water tank to flow in parallel partly through the preheat tank and partly through the bypass line. The effect was to reduce the performance of the solar system an indeterminable amount.

The Remote Solar Assembly which supports the collector array was installed near a dirt drive way. As a result the collectors and pyranometer were generally covered with dust. This could have reduced the radiation measurements of the pyranometer and reduced the radiation absorption capability of the collectors.

The performance assessment data was selected from the available site data which was available from October, 1978, through March, 1980. It was initially planned to use January, 1979, through December, 1979, data for the assessment. However, because of large data voids in January, March, November and December, 1979, data from 1978 and 1980 were substituted for those months.

3.1 System Performance

This Seasonal Report provides a system performance evaluation summary of the operation of the IBM System 4 Solar Energy System located in Clinton, Mississippi. Analysis was conducted by evaluation of measured system performance against the expected performance with long-term average climatic conditions. The performance of the system is evaluated by calculating a set of primary performance factors which are based on those proposed in the intergovernmental agency report, "Thermal Data Requirements and Performance Evaluation Procedures for the National Solar Heating and Cooling Demonstration Program" [4]. The performance of the major subsystems is also evaluated in subsequent section of this report.

Measurement data for the site is available from October, 1978, through March, 1980. The data used for this performance evaluation was selected so as to use data from months that contained the most complete set of site measured data.

System performance data were provided through an IBM developed Central Data Processing System (CDPS) [5] consisting of a remote Site Data Acquisition System (SDAS), telephone data transmission lines and couplers, an IBM System 7 computer for data management, and an IBM System 370/145 computer for data processing. The CDPS supports the collection and analysis of solar data acquired from instrumented systems located throughout the country. These data are processed daily and summarized into monthly performance formats which form a common basis for comparative system evaluation. These monthly summaries are the basis of the evaluation and data given in this report.

The solar energy system performance summarized in this section can be viewed as the dependent response of the system to certain primary inputs. This relationship is illustrated in Figure 3.1-1. The primary inputs are the incident solar energy, the outdoor ambient temperature and the system load. The dependent responses of the system are the system solar fraction and the total energy savings. Both the input and output definitions are as follows:

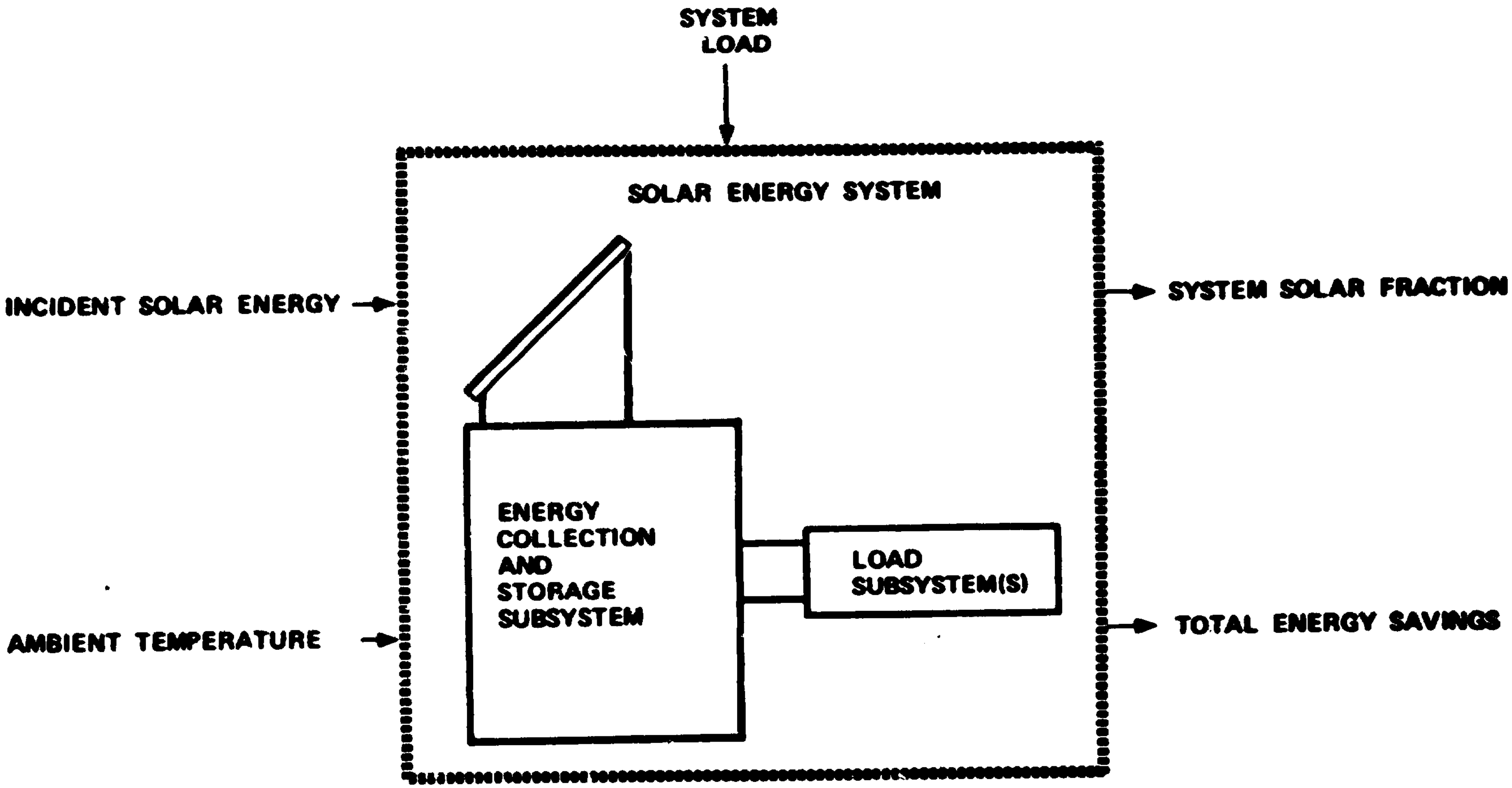


Figure 3.1-1 Solar Energy System Evaluation Block Diagram

Inputs

- Incident solar energy - The total solar energy incident on the collector array and available for collection.

- Ambient temperature - The temperature of the external environment which affects both the energy that can be collected and the energy demand.

- System load - The loads that the system is designed to meet, which are affected by the life style of the user (space heating/cooling, domestic hot water, etc., as applicable).

Outputs

- System solar fraction - The ratio of solar energy applied to the system loads to total energy (solar plus auxiliary energy) required by the loads.

- Total energy savings - The quantity of auxiliary energy (electrical or fossil) displaced by solar energy.

The monthly values of the inputs and outputs for the total operational period are shown in Table 3.1-1, the System Performance Summary. Comparative long-term average values of daily incident solar energy, and outdoor ambient temperature are given for reference purpose. The long-term data are taken from Reference 1 of Appendix C. Generally the solar energy system is designed to supply an amount of energy that results in a desired value of system solar fraction while operating under climatic conditions that are defined by the long-term average value of daily incident solar energy and outdoor ambient temperature. If the actual climatic conditions are close to the long term average values, there is little adverse impact on the system's ability to meet design goals. This is an important factor in evaluating system performance and is the reason the long-term average values are given. The data reported in the following paragraphs are taken from Table 3.1-1.

TABLE 3.1-1

SYSTEM PERFORMANCE SUMMARY

IBM 4 CLINTON

Month	Daily Incident Solar Energy per Unit Area (45° Tilt) (Btu/Ft^2-Day)		Ambient Temperature (°F)		System Load Measured	Solar Fraction (Percent)		Total Energy Savings
	Measured	Long-Term Average	Measured	Long-Term Average	(Million Btu)	Measured	Expected	(Million Btu)
Jan 80	635	1124	47	47	6.06	21	6	0.78
Feb 79	835	1351	45	50	8.56	15	6	0.40
Mar 80	1073	1529	54	56	4.67	44	28	1.65
Apr 79	1284	1592	67	66	0.61	27	33	0.40
May 79	1402	1575	72	73	0.52	10	42	0.48
Jun 79	1389	1543	79	79	0.28	61	42	0.13
Jul 79	1237	1501	81	82	0.33	48	31	0.10
Aug 79	1492	1565	80	81	0.22	58	32	-0.02
Sep 79	1382	1570	74	76	0.08	41	20	-0.05
Oct 79	1769	1629	65	66	1.08	71	69	0.75
Nov 78	1031	1345	59	55	2.37	61	44	1.35
Dec 78	1148	1110	47	49	6.72	39	23	2.08
Total	--	--	--	--	31.49	--	--	8.05
Average	1223	1453	64	65	2.62	32*	20*	0.67

*Averages are weighted values.

At the IBM System 4 site for the 12 month period, the long-term average daily incident solar energy in the plane of the collector was 1,453 Btu/Ft^2. The average daily measured value was 1,223 Btu/Ft^2, which is 16 percent below the long-term value. On a monthly basis January, 1980, was the worst month with an average daily measured value of incident solar energy 44 percent below the long-term average daily value. October, 1979, was the best month with an average daily measured value 9 percent above the long-term average daily value. On a long-term basis it can be concluded that the long-term average performance would be slightly higher than the measured performance based on the difference between long-term and measured average incident solar energy.

The outdoor ambient temperature influences the operation of the solar energy system in two important ways. First the operating point of the collectors and consequently the collector efficiency or energy gain is determined by the difference in the outdoor ambient temperature and the collector inlet temperature. This will be discussed in greater detail in Section 3.2.1. Secondly the load is influenced by the outdoor ambient temperature. The long-term average daily ambient temperature for the 12 month period was 65°F at the IBM System 4 site. This agrees closely with the measured value which was 64°F.

The system design values for the IBM System 4 at Clinton were a total system solar fraction of 48 percent which includes a space heating solar fraction of 35 percent and a hot water solar fraction of 63 percent.

The measured value of system solar fraction do not generally agree favorably with the expected values computed by the modified f-Chart method. The reason for this is that the modified f-Chart method uses some assumptions that do not fit this solar system. The original f-Chart system neglects system heat losses and presumes heat losses from the solar system ultimately contribute to the system heating load. Certain losses from IBM System 4 are lost to the ambient and definitely do not contribute to the space heating subsystem load. The modified f-Chart method accounts for these losses for a standard solar system. Variation between this standard system and IBM System 4 apparently cause the difference between the measured and expected solar fractions.

The total energy savings is the most important performance parameter for the solar energy system because the fundamental purpose of the system is to replace expensive conventional energy sources with less expensive solar energy. In practical consideration, the system must save enough energy to cover both the cost of its own operation and to repay the initial investment for the system. In terms of the technical analysis presented in this report the net total energy savings should be a significant positive figure. The total computed energy savings for the IBM System 4 Solar Energy System was 7.70 million Btu, which is equivalent to 2256 kWh, or 1.3 barrels of oil, which was not a large amount of energy. However, this savings is based only on measured inputs of solar energy to the load subsystem. At the IBM System 4 site the hot water consumption was considerably lower than expected, which of course resulted in much lower savings than expected. This condition is addressed in more detail in the appropriate sections that follow.

3.2 Subsystem Performance

The IBM System 4 Solar Energy System may be divided into four subsystems:

1. Collector array
2. Storage
3. Hot Water
4. Space heating

Each subsystem has been evaluated by the techniques defined in Section 3 and is numerically analyzed each month for the monthly performance assessment. This section presents the results of integrating the monthly data available on the four subsystems for a one year period as follows:

January, 1980
February, 1979
March, 1980
April, 1979
May, 1979
June, 1979
July, 1979
August, 1979
September, 1979
October, 1979
November, 1978
December, 1978

Portions of the collector array analysis used data from the year 1979 exclusively. These areas are noted accordingly in subsequent discussions.

3.2.1 Collector Array Subsystem

The IBM System 4 collector array consists of twelve Solaron 2001 series flat-plate air collectors. The collector is 3 feet wide by 6.5 feet long by 7.2 inches high and weighs 153 pounds. The collector is double glazed with 1/8 inch thick low iron safety glass (Forco) having a total transmittance of 0.77. The absorber is 24 gauge steel with a PPG "Duracron 600" surface finish. The absorptivity and emmissivity of the absorber is 0.94 and 0.82 respectively. The back surface insulation of the collector is 1 inch thick, 2 pounds per cubic foot fiberglas batt. The collectors are arranged in an array 2 collectors high by 6 collectors wide. Collector air manifolding is arranged into two externally manifolded groups with each of the two groups internally manifolded. This manifolding results in 6 parallel air paths through the array with an air flow rate of 77 cubic feet per minute through each path. Therefore, the air flow rate through each collector is 77 cubic feet per minute. Details of the collector and collector array "flow" paths are shown in Figure 3.2.1-1. The collector array is oriented as follows:

Tilt	- 45°
Azimuth	- Due South
Location	- 32' 19" Latitude/88' 45" Longtitude

The collector subsystem analysis and data are given in the following paragraphs.

Collector array performance is described by the collector array efficiency. This is the ratio of collected solar energy to incident solar energy, a value always less than unity because of collector losses. The incident solar energy may be viewed from two perspectives. The first assumes that all available solar energy incident on the collectors must be used in determining collector array efficiency. The efficiency is then expressed by the equation:

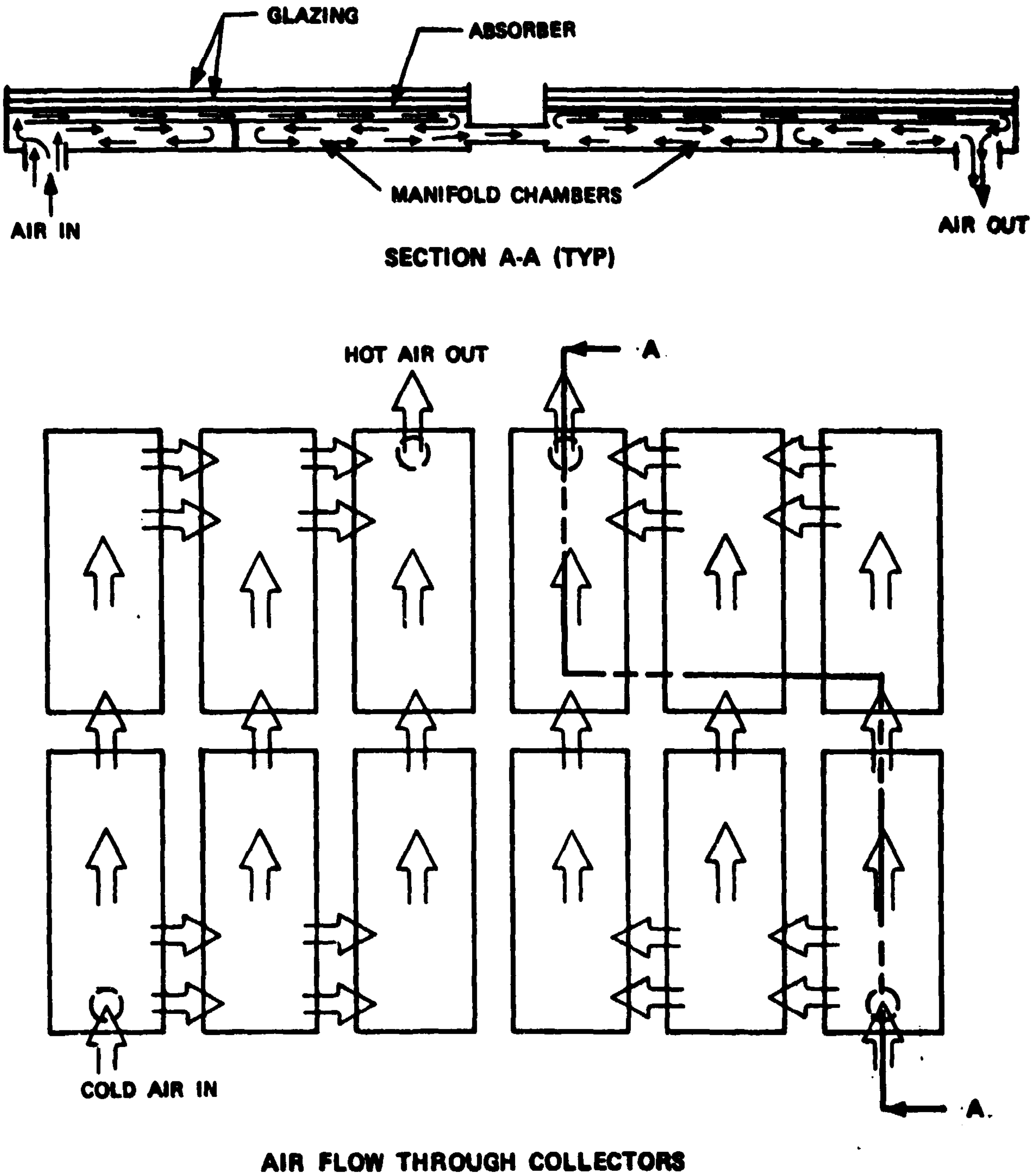


Figure 3.2.1-1 Collector Array Air Flow

$$\eta_c = Q_s/Q_i \qquad (1)$$

where η_c = Collector array efficiency

Q_s = Collected solar energy

Q_i = Incident solar energy

The efficiency determined in this manner includes the operation of the control system. For example, solar energy can be available at the collector, but the collector absorber plate temperature may be below the minimum control temperture set point for collector loop operation, thus the energy is not collected. The monthly efficiency by this method is listed in the column entitled "Collector Array Efficiency" in Table 3.2.1-1.

The second viewpoint assumes that only the solar energy incident on the collector when the collector loop is operational be used in determining the collector array efficiency. The value of the operational incident solar energy used is multiplied by the ratio of the gross collector area to the gross collector array area to compensate for the difference between the two areas caused by installation spacing. The efficiency is then expressed by the equation:

$$\eta_{co} = Q_s/(Q_{oi} \times A_p/A_a) \qquad (2)$$

where η_{co} = Operational collector array efficiency

Q_s = Collected solar energy

Q_{oi} = Operational incident solar energy

A_p = Gross collector area (the product of the number of collectors and the envelope area of one collector)

A_a = Gross collector array area (total area including all mounting and connecting hardware and spacing of units)

TABLE 3.2.1-1

COLLECTOR ARRAY PERFORMANCE

Month	Incident Solar Energy (Million Btu)	Collected Solar Energy (Million Btu)	Collector Array Efficiency	Operational Incident Energy (Million Btu)	Operational Collector Array Efficiency*
Jan 80	5.10	1.53	0.30	3.90	0.43
Feb 79	6.06	1.88	0.31	4.82	0.43
Mar 80	8.62	2.57	0.30	7.06	0.40
Apr 79	9.98	1.68	0.17	5.79	0.32
May 79	11.26	1.46	0.13	5.48	0.29
Jun 79	10.79	2.39	0.22	7.62	0.34
Jul 79	9.94	2.15	0.22	6.80	0.35
Aug 79	11.99	2.66	0.22	8.43	0.35
Sep 79	10.74	1.84	0.17	6.34	0.32
Oct 79	14.21	2.39	0.17	8.53	0.31
Nov 78	8.01	2.03	0.25	5.67	0.40
Dec 78	9.22	3.19	0.34	8.08	0.43
Total	115.92	25.77	--	78.52	--
Average	9.66	2.15	0.23	6.54	0.36

*Operational Collector Array Efficiency Values are adjusted for the ratio of Ap/Aa as indicated in Equation (2).

The monthly efficiency computed by this method is listed in the column entitled "Operational Collector Array Efficiency" in Table 3.2.1-1.

In the ASHRAE Standard 93-77 [6] a collector efficiency is defined in the same terminology as the operational collector array efficiency. However, the ASHRAE efficiency is determined from instantaneous evaluation under tightly controlled, steady state test conditions, while the operational collector array efficiency is determined from actual dynamic conditions of daily solar energy system operation in the field.

The ASHRAE Standard 93-77 definitions and methods often are adopted by collector manufacturers and independent testing laboratories in evaluating collectors. The collector evaluation performed for this report using the field data indicates that there was a significant difference between laboratory calibrated single panel collector data and the collector data determined from long-term field measurements. There are two primary reasons for differences in the laboratory and field data:

- Test conditions are not the same as conditions in the field, nor do they represent the wide dynamic range of field operation (i.e. inlet and outlet temperature, flow rates and flow distribution of the heat transfer fluid, insolation levels, aspect angle, wind conditions, etc.)

- Collector tests are not generally conducted with units that have undergone the effects of aging (i.e. changes in the characteristics of the glazing material, collection of dust, soot, pollen or other foreign material on the glazing, deterioration of the absorber plate surface treatment, etc.)

Consequently field data collected over an extended period will generally provide an improved source of collector performance characteristics for use in long-term system performance definition.

The long-term data base for IBM 4 Clinton detailed collector analysis includes all data collected for the year 1979. Eight more months of data were available for analysis; however, data from the twelve months of 1979 were considered adequate.

The operational collector array efficiency data given in Table 3.2.1-1 are monthly averages based on instantaneious efficiency computations over the total performance period using all available data. For detailed collector analysis it was desirable to use a limited subset of the available data that characterized collector operation under "steady state" conditions. This subset was defined by applying the following restrictions:

(1) The measurement period was restricted to collector operation when the sun angle was within 30 degrees of the collector normal.

(2) Only measurements associated with positive energy gain from the collectors were used, i.e., outlet temperatures must have exceeded inlet temperatures.

(3) The sets of measured parameters were restricted to those where the rate of change of all parameters of interest during two regular data system intervals* was limited to a maximum of 5 percent.

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*The data system interval was 5-1/3 minutes in duration. Values of all measured parameters were continuously sampled at this rate throughout the performance period.

Instantaneous efficiencies (η_j) computed from the "steady state" operation measurements of incident solar energy and collected solar energy by Equation (2)* were correlated with an operating point determined by the equation:

$$x_j = \frac{T_i - T_a}{I} \tag{3}$$

where x_j = Collector operating point at the j^{th} instant

T_i = Collector inlet temperature

T_a = Outdoor ambient temperature

I = Rate of incident solar radiation

The data points (η_j, x_j) were then plotted on a graph of efficiency versus operating point and a first order curve described by the slope-intercept formula was fitted to the data through linear regression techniques. The form of this fitted efficiency curve is:

$$\eta_j = b - mx_j \tag{4}$$

where η = Collector efficiency corresponding to the j^{th} instant

b = Intercept on the efficiency axis

$(-)m$ = Slope

x_j = Collector operating point at j^{th} instant

The relationship between the empirically determined efficiency curve and the analytically developed curve will be established in subsequent paragraphs.

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*The ratio A_p/A_a is assumed to be unity for this analysis.

The analytically developed collector efficiency curve is based on the Hottell-Whillier-Bliss equation:

$$\eta = F_R(\tau\alpha) - F_R U_L \left(\frac{T_i - T_a}{I}\right) \tag{5}$$

where η = Collector efficiency

F_R = Collector heat removal factor

τ = Transmissivity of collector glazing

α = Absorptance of collector plate

U_L = Overall collector energy loss coefficient

T_i = Collector inlet fluid temperature

T_a = Outdoor ambient temperature

I = Rate of incident solar radiation

The correspondence between equations (4) and (5) can be readily seen. Therefore by determining the slope-intercept efficiency equation from measurement data, the collector performance parameters corresponding to the laboratory single panel data can be derived according to the following set of relationships:

$$b = F_R\tau\alpha \quad \text{and} \quad m = F_R U_L \tag{6}$$

where the terms are as previously defined

The discussion of the collector array efficiency curves in subsequent paragraphs is based upon the relationships expressed by Equation (6).

In deriving the collector array efficiency curves by the linear regression technique, measurement data over the entire performance period yields higher confidence in the results than similar analysis over shorter periods. Over the longer periods the collector array is forced to operate over a wider dynamic range. This eliminates the tendency shown by some types of solar energy systems* to cluster efficiency values over a narrow range of operating points. The clustering effect tends to make the linear regression technique approach constructing a line through a single data point. The use of data from the entire performance period results in a collector array efficiency curve that is more accurate in long-term solar system performance prediction. The long-term curve and the curve derived from the laboratory single panel data are shown in Figure 3.2.1-2.

The long-term first order curve shown in Figure 3.2.1-2 has a slightly higher negative slope than the curve derived from single panel laboratory test data. This is attributable to higher losses (other than leakage) resulting from array effects. The laboratory predicted instaneous efficiency is not in close agreement with the curve derived from actual field operation. This indicates that the laboratory derived curve might not be useful for design purposes in an array configuration of this type. However, this statement must be tempered by the fact that actual performance might approach predicted performance more closely if there were no leakage problems with the collector array or ductwork. Additionally a higher collector air flow rate in the collector array would have increased the overall efficiency. The laboratory test was performed with an air flow rate of 4 cubic feet per minute per square foot of collector, whereas the IBM 4 Clinton collector flow rate averaged about 3.5 cubic feet per minute per square foot of collector.

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*Air collector/rock storage systems show a marked tendency toward clustering because the collector inlet temperature remains relatively constant and the range of values of ambient temperature and incident solar energy during collector operation are also relatively restricted on a short-term basis.

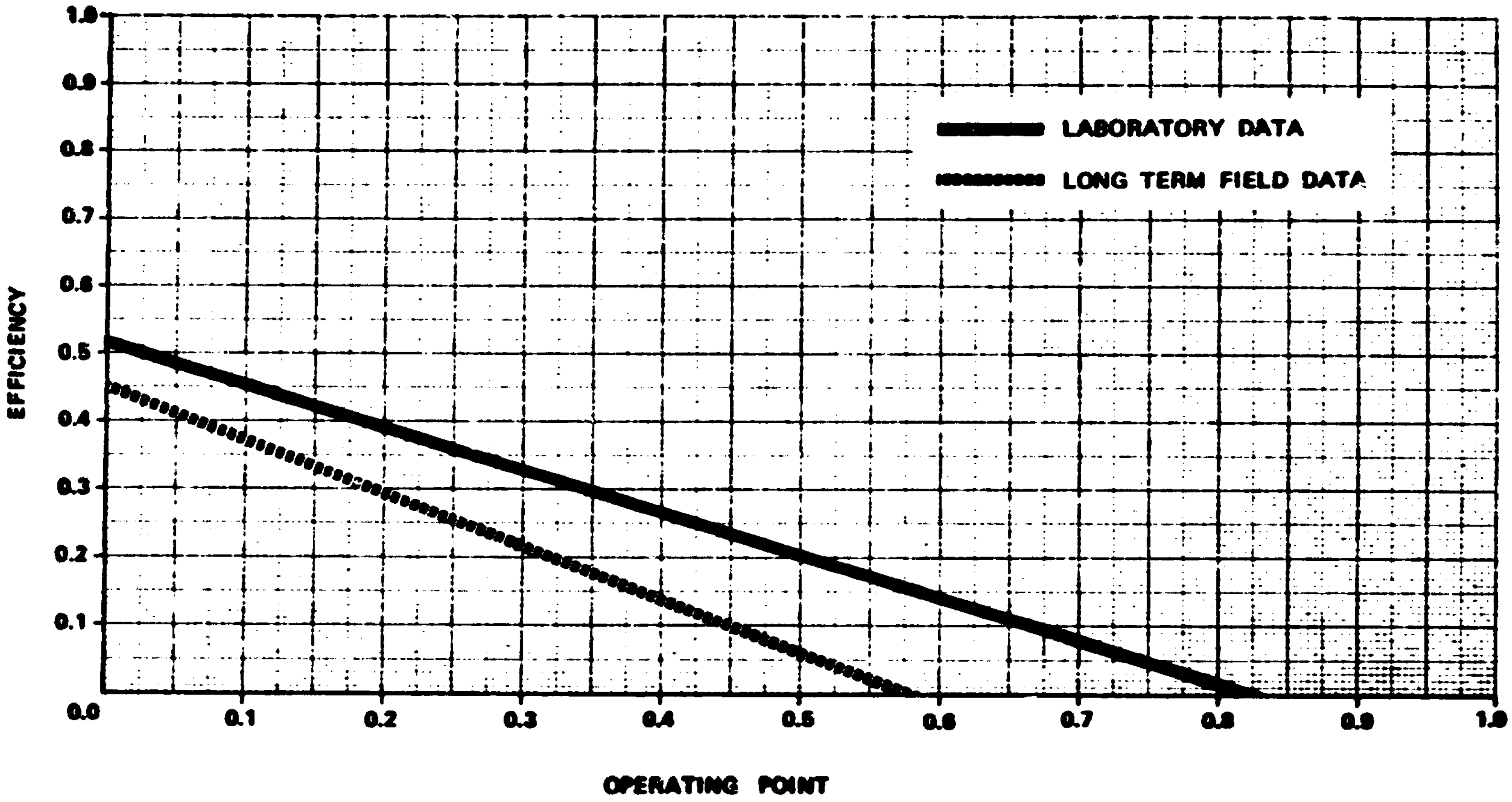


Figure 3.2.1-2 IBM System 4 Collector Efficiency Curve

For information purposes the data associated with Figure 3.2.1-2 is as follows:

Single panel laboratory data

$F_R(\tau\alpha) \quad = \quad 0.520 \qquad\qquad F_R U_L = \quad = \quad -0.630$

Long-term field data

$F_R(\tau\alpha) \quad = \quad 0.455 \qquad\qquad F_R U_L \quad = \quad -0.806$

Table 3.2.1-2 presents data comparing the monthly measured values of solar energy collected with the predicted performance determined from the long-term regression curve and the laboratory single panel efficiency curve. The predictions were derived by the following procedure:

1. The instantaneous operating points were computed using Equation (3).

2. The instantaneous efficiency was computed using Equation (4) with the operating point computed in Step 1 above for:

   a. The long-term linear regression curve for collector array efficiency

   b. The laboratory single panel collector efficiency curve

3. The efficiencies computed in Steps 2a and 2b above were multiplied by the measured solar energy available when the collectors were operational to give two predicted values of solar energy collected.

TABLE 3.2.1-2

ENERGY GAIN COMPARISON
(ANNUAL)

SITE: IBM 4 CLINTON CLINTON, MISSISSIPPI

Month	Collected Solar Energy (Million Btu)	Error	
		Field Derived Long-Term	Laboratory Single Panel
Jan 79	1.808	0.050	-0.006
Feb 79	1.684	0.03[illegible]	-0.065
Mar 79	1.427	0.030	-0.135
Apr 79	1.649	0.065	-0.164
May 79	1.428	0.111	-0.166
Jun 79	2.523	0.069	-0.148
Jul 79	2.246	0.081	-0.142
Aug 79	2.649	0.082	-0 146
Sep 79	1.754	0.078	-0.181
Oct 79	1.805	0.069	-0.205
Nov 79	2.815	0.042	-0.139
Dec 79	1.975	0.189	-0.038
Average	1.980	0.075	-0.128

The error data in Table 3.2.1-2 were computed from the differences between the measured and predicted values of solar energy collected according to the equation:

$$\text{Error} = (A-P)/P \qquad (7)$$

where A = Measured solar energy collected
P = Predicted solar energy collected

The computed error is then an indication of how well the particular prediction curve fitted the reality of dynamic operating conditions in the field.

The values of "Collected Solar Energy" given in Table 3.2.1-2 are not necessarily identical with the values of "Collected Solar Energy" given in Table 3.2.1-1. Any variations are due to the differences in data processing between the software programs used to generate the monthly performance assessment data and the component level collector analysis program. Also data for January, March, November, and December were taken from different years as noted. These data are shown in Table 3.2.1-2 only because they form the references from which the error data given in the table are computed.

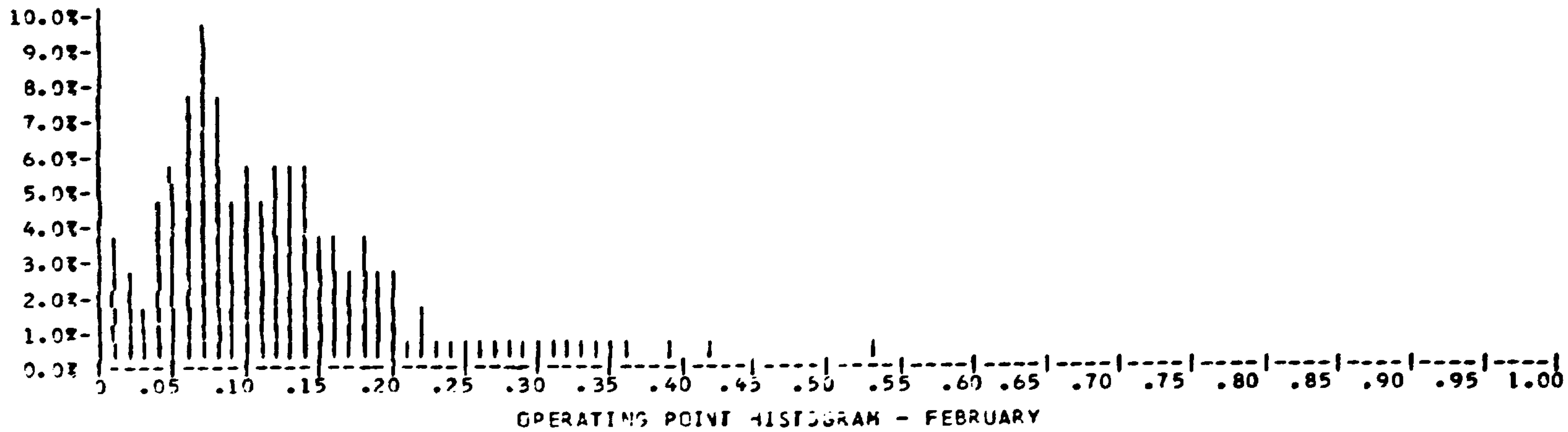
The data from Table 3.2.1-2 illustrates that for the IBM 4 Clinton site the average error computed from the difference between the measured solar energy collected and the predicted solar energy collected based on the field derived long-term collector array efficiency curve was 7.5 percent. For the curve derived from the laboratory single panel data, the error was -12.8 percent. Thus the long-term collector array efficiency curve gives slightly better results than the laboratory single panel curve.

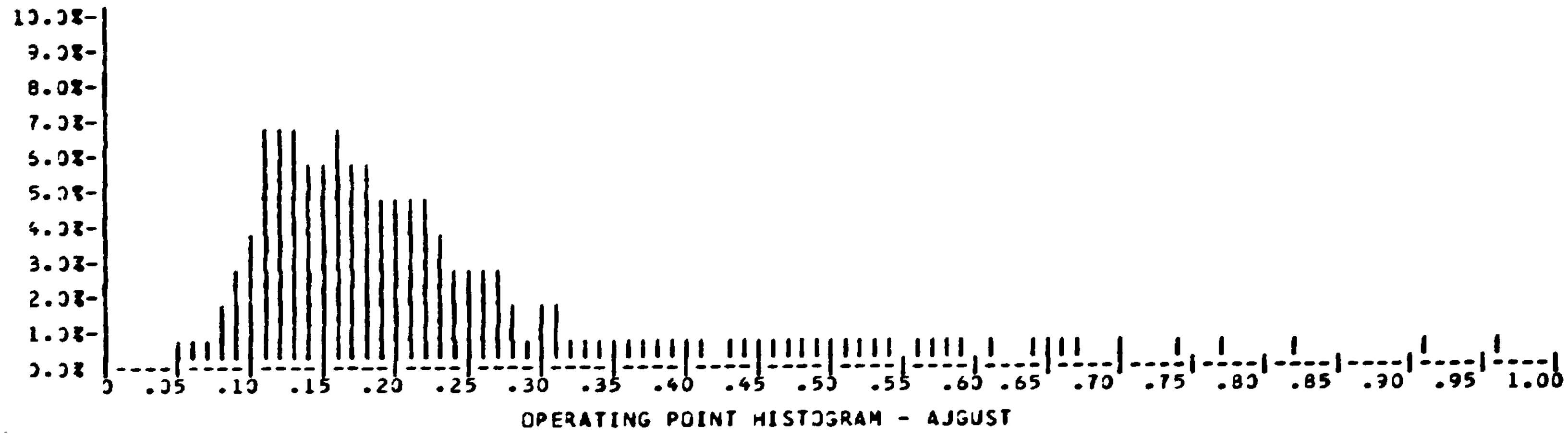
A histogram of collector array operating points illustrates the distribution of instantaneous values as determined by Equation (3) for the entire month. The histogram was constructed by computing the instantaneous operating point value from site instrumentation measurements at the regular data system intervals throughout the month, and counting the number of values within contiguous intervals of width 0.01 from zero to unity. The operating point histogram shows the dynamic range of collector operation during the month from which the midpoint can be ascertained. The average collector array efficiency for the month can then be derived by projecting the midpoint value to the appropriate efficiency curve and reading the corresponding value of efficiency.

Another characteristic of the operating point histogram is the shifting of the distribution along the operating point axis. This can be explained in terms of the characteristics of the system and the climatic factors of the site, i.e., incident solar energy and ambient temperature. Figure 3.2.1-3 shows two histograms that illustrate a typical winter month (February) and a typical summer month (August) operation. The approximate average operating point for February is at 0.10 and for August at 0.17. From Equation (3), when the temperature difference becomes larger between T_i and T_a, and the incident solar energy becomes smaller, as is typical in the winter, the operating point increases and collector operation shifts to the right on the operating point histogram. The opposite situation occurs in the summer. Normally, the important point to be made from this is that the average collector efficiency, which depends on the operating point, shifts from winter to summer, assuming the higher value in the summer. The typical winter and summer average monthly operating points for this site as shown in Figure 3.2.1-3 indicates that there is a slight reversal of this expected trend. The average monthly collector array efficiency for the year under study as shown in Table 3.2.1-1 also shows a reversal from the expected trend. The operating point reversal is suspected to be caused by collector array leakage that lowers the air temperature (T150) and lowers the actual flow through the collector array.

IBM 4 CLINTON CLINTON, MS

COLLECTOR TYPE: SOLARON COLLECTOR MODEL: 2000





ABCISSA = (INLET TEMP - AMBIENT TEMP)/INSOLATION DEG F - HR - SQFT/BTU
ORDINATE = PERCENT OF TOTAL OCCURRENCES

Figure 3.2.1-3 IBM System 4 Operating Point Histogram for Typical Winter and Summer Months

Also the incident energy on the array is affected by the array tilt angle which is 45°. The array is therefore tilted 13° above the site latitude which favors winter incidence absorption.

Table 3.2.1-1 presents the monthly values of incident solar energy, operational incident solar energy, and collected solar energy from the 12 month performance period. The collector array efficiency and operational collector array efficiency were computed for each month using Equations (1) and (2). On the average the operational collector array efficiency exceeded the collector array efficiency, which included the effect of the control system, by 57 percent.

Additional information concerning collector array analysis in general may be found in Reference [8]. The material in the reference describes the detailed collector array analysis procedures and presents the results of analyses performed on numerous collector array installations across the United States.

3.2.2 Storage Subsystem

Storage subsystem performance is described by comparison of energy to storage, energy from storage and change in stored energy. The ratio of the sum of energy from storage and change in stored energy to energy to storage is defined as storage efficiency, η_s. This relationship is expressed in the equation

$$\eta_s = (\Delta Q + Q_{so})/Q_{si} \tag{8}$$

where:

ΔQ = Change in stored energy. This is the difference in the estimated stored energy during the specified reporting period, as indicated by the relative temperature of the storage medium (either positive or negative value)

Q_{so} = Energy from storage. This is the amount of energy extracted by the load subsystem from the primary storage medium

Q_{si} = Energy to storage. This is the amount of energy (both solar and auxiliary) delivered to the primary storage medium

Evaluation of the system storage performance under actual system operation and weather conditions can be performed using the parameters defined above. The utility of these measured data in evaluation of the overall storage design are illustrated in the following discussion.

Table 3.2.2-1 summarizes the storage subsystem performance during the report period.

During the 12 month period of study a total of 22.37 million Btu was delivered to the rock storage and a total of 14.12 million Btu was removed for support of system loads or rejected. The net change in stored energy during this same time period was -0.17 million Btu, which leads to a storage efficiency of 0.59 and a total energy loss from storage of 8.42 million Btu.

The computed storage efficiency of 0.59 is relatively low as compared to many solar energy systems. However, the average storage temperature during the period that efficiency was computed was 122°F, so the low value of efficiency is reasonable. Heat losses are directly proportional to the temperature difference between the inside average storage temperature and the average ambient temperature. This temperature difference was 55°F for the period studied. This value is realtively high and accounts for the somewhat low storage efficiency. The storage unit is considered well insulated since the effective heat transfer coefficient averaged only 16.5 Btu/Hr°F during the period studied.

TABLE 3.2.2-1

STORAGE SUBSYSTEM PERFORMANCE

Month	Energy To Storage (Million Btu)	Energy From Storage (Million Btu)	Change In Stored Energy (Million Btu)	Storage Efficiency	Storage Average Temperature (F°)
Jan 80	1.61	1.24	-0.01	0.76	76
Feb 79	2.47	1.13	-0.01	0.45	79
Mar 80	2.35	1.70	0.07	0.75	95
Apr 79	1.37	1.04	0.08	0.82	139
May 79	1.07	0.00	-0.06	-0.06	151
Jun 79	1.83	1.26	0.02	0.70	136
Jul 79	1.67	1.07	0.00	0.64	135
Aug 79	2.14	1.55	0.00	0.72	138
Sep 79	1.51	0.58	0.07	0.43	148
Oct 79	1.84	0.73	-0.06	0.36	155
Nov 78	1.67	1.35	-0.22	0.68	117
Dec 78	2.84	2.47	-0.05	0.85	89
Total	22.37	14.12	-0.17	--	--
Average	1.86	1.18	-0.01	0.59	122

3.2.3 Hot Water Subsystem

The performance of the hot water subsystem is described by comparing the amount of solar energy supplied to the subsystem with the energy required to satisfy the total hot water load. The energy required to satisfy the total load consists of both solar energy and auxiliary thermal energy.

The performance of the IBM System 4 hot water subsystem is presented in Table 3.2.3-1. The value for auxiliary energy supplied in Table 3.2.3-1 is the gross energy supplied to the auxiliary system. The value of auxiliary energy supplied multiplied by the auxiliary system efficiency gives the auxiliary thermal energy actually delivered to the load. The difference between the sum of auxiliary thermal energy plus solar energy and the hot water load is equal to the thermal (standby) losses from the hot water subsystem.

The measured solar fraction in Table 3.2.3-1 is an average weighted value for the month based on the ratio of solar energy in the hot water tank to the total energy in the hot water tank when a demand for hot water exists. This value is dependent on the daily profile of hot water usage. It does not represent the ratio of solar energy supplied to the sum of solar plus auxiliary energy supplied shown in the Table.

For the 12 month period described in Table 3.2.3-1 the solar energy system supplied a total of 3.67 million Btu to the hot water load. The total hot water load for this period was 3.48 million Btu, and the weighted average monthly solar fraction was 33 percent.

The monthly average hot water load during the reporting period was 0.29 million Btu. This is based on an average daily consumption of 20 gallons, delivered at an average temperature of 126°F and supplied to the system at an average temperature of 72°F. The temperature of the supply water ranged from a low of 59°F in February to a high of 83°F in August.

Each month an average of 0.31 million Btu of solar energy and 0.41 million Btu of auxiliary thermal (electrical) energy were supplied to the hot water subsystem. Since the average monthly hot water load was 1.29 million Btu, an average of 0.43 million Btu was lost from the preheat and hot water tanks each month.

TABLE 3.2.3-1

HOT WATER SUBSYSTEM PERFORMANCE

Month	Hot Water Parameters				Energy Consumed (Million Btu)			Weighted Solar Fraction (Percent)
	Load (Million Btu)	Gallons Used	Temperatures (°F) Supply	Temperatures (°F) Delivery	Solar	Auxiliary Thermal	Auxiliary	
Jan 80	0.13	206	68	129	0.16	0.40	0.40	18
Feb 79	0.15	288	59	114	0.26	0.36	0.36	24
Mar 80	0.13	246	62	128	0.22	0.34	0.34	30
Apr 79	0.51	835	69	141	0.13	0.77	0.77	13
May 79	0.52	737	77	128	0.24	0.84	0.84	10
Jun 79	0.28	939	79	117	0.44	0.19	0.19	61
Jul 79	0.33	877	82	128	0.36	0.29	0.29	48
Aug 79	0.22	615	83	126	0.39	0.28	0.28	58
Sep 79	0.08	197	77	124	0.22	0.24	0.24	41
Oct 79	0.40	972	71	127	0.53	0.33	0.33	53
Nov 78	0.46	1019	72	121	0.29	0.41	0.41	29
Dec 78	0.26	420	67	128	0.38	0.47	0.47	33
Total	3.48	7351	--	--	3.67	4.92	4.92	--
Average	0.29	613	72	126	0.31	0.41	0.41	33

Hot water solar fraction is not only a result of the particular hot water solar system design but it is also a result of many site imposed installation and hot water utilization characteristics. The relatively low hot water solar fraction for IBM 4 Clinton is caused by several factors related to site characteristics as follows:

- Extremely low water consumption
- Sporadic hot water consumption
- Frequent leaky hot water faucets
- Long pipe lines between preheat tank and hot water tank

The initial estimated hot water demand for the Clinton site was 130 gallons per day. Based on this demand and assuming no solar energy lost from the system, a hot water solar fraction of 63 percent was calculated by f-Chart for the initial System Performance Specification Reference [10]. An analysis using 25 gallons per day with f-Chart would have given a 71 percent hot water solar fraction which is even higher. The reason for the discrepancy between the calculated and measured hot water solar fraction is that the original f-Chart does not take energy losses into account when predicting hot water solar fraction. There are many solar system design parameters which can affect these losses. Insulation of the air to water heat exchanger, preheat tank, and interconnecting pipe lines between these items and the hot water tank can definitely affect performance, but insulation of these items is considered adequate. The design characteristic which does affect performance is the serial flow arrangement between the preheat tank and the hot water tank. The only way solar energy can get to the hot water tank is by a hot water draw. Because site occupancy was periodic, hot water demand was frequently non-existent. At that time only auxiliary energy was supplied to DHW tank to make up for heat losses even though hot water may have been available at a higher temperature in the preheat tank.

The pipe lines from the preheat tank to the south bath and north bath were approximately 100 and 170 feet respectively. The heat lost from these lines was increased by the frequent hot water faucet leaks. At the low leak rate of about 25 gallons per day, hot water which left the preheat tank was cold by the time it reached the hot water tanks. Thus, most if not all of the solar energy was lost.

The low demand for hot water resulted in the loss of most of the solar heat supplied to the preheat tank. Also, if water is not drawn from the preheat tank it quickly reaches temperature and thermosyphoning action ceases so the full capability of the system is not realized. This affected the energy savings.

Solar hardware performance also affects the hot water solar fraction. Performance of the solar collector array was discussed in Section 3.2.1. The array efficiency in that section was shown to be significantly less than the single panel laboratory test collector efficiency used in the original f-Chart prediction. Therefore, with less energy being collected than originally calculated the hot water solar fraction would be lower than originally predicted.

The summer mode operation of the system did not perform as well as expected. Special site equations were written to obtain several parameters from which the performance could be evaluated. Energy removed from storage, energy transferred to preheat tank and collector blower operating energy were calculated to obtain the parameters for the period of the summer mode of operation. The following table is a summary of this analysis.

Month	Energy Removed From Storage (Btu Thousands)	Energy Supp. 'd Preheat Tank (BtU Thousands)	Blower Operating Energy (Btu Thousands)
June 79	1259	23	90
July 79	1072	14	73
August 79	1550	19	106
Total	3881	56	269

The data shows that four times as much energy was expended to operate the blowers than the energy gathered in the preheat tank. Also sixty times as much energy was removed from rock storage as was gathered in the preheat tank.

Two intangible benefits were achieved by dumping energy from storage in the summer mode. First, without dumping energy in the evening, the collector blower operation in the morning would quickly raise the preheat tank or rock storage to their maximum allowable temperature and then shut down for the remainder of the day. If rock storage remained above the maximum allowable temperature (200°F) the collector blower would not run even though the preheat tank is depleted of hot water. The collector absorber temperature rises to very high temperature in this stall condition. Collector efficiency deterioration has been measured for these collectors when they were subjected to a one year weathering test as reported in Reference [12]. Removing heat from storage in the evening insures that the collector blower will operate during the day light hours and therefore eliminates the problem associated with the collector stall condition. This continual operation during the day gives an additional benefit in that it extends the day time period when solar energy can be transferred to the preheat tank.

During summer mode operation in the evening there is approximately a 30°F temperature drop across the collector. Normally the energy loss which causes this temperature drop would be caused by collector radiation loss and back side conduction losses; however, both of these are not expected

to cause the 30°F temperature drop. Losses because of air leakage into the array is expected to contribute heavily to this energy loss. In order for the summer mode to be effective these losses must be eliminated. If the losses can not be eliminated, the summer mode of operation can be simply eliminated by leaving the summer mode switch in the off position. Also, the controller and sensors allocated to the summer mode could be removed and used for some other purpose. Since it is identical to the primary controller it can be used as a back-up.

3.2.4 Space Heating Subsystem

The performance of the space heating subsystem is described by comparing the amount of solar energy supplied to the subsystem with the energy required to satisfy the total space heating load. The energy required to satisfy the total load consists of both solar energy and auxiliary thermal energy. The ratio of solar energy supplied to the load to the total load is defined as the heating solar fraction. The calculated heating solar fraction is the indicator of performance for the subsystem because it defines the percentage of the total space heating load supported by solar energy.

The performance of the IBM 4 Clinton space heating subsystem is presented in Table 3.2.4-1. For the 12 month period under study, the solar energy system supplied a total of 8.96 million Btu to the space heating load. The total heating load for this period was 28.01 million Btu, and the average monthly solar fraction was 32 percent.

Space heating load and space heating solar fraction that were calculated for this site by f-Chart during the design phase were 30.69 million Btu and 35 percent respectively. These were reported in Reference [10] and were based on long-term insolation, long-term weather data for Jackson, Mississippi, and a design UA value for the building of 556 Btu/Hr°F.

The measured space heating load of 28.01 million Btu and solar fraction of 32 percent are in close agreement to the calculated values. The long-term available radiation of 8.80 million Btu agrees favorably with the measured value of 8.74 million Btu. The long-term heating degree day value of 2,300 is 10% below the measured heating degree day value of 2,530. This increased measured load partially accounts for the reduction in the space heating solar fraction.

This system has storage and auxiliary heat arranged in series. This requires return air to pass through storage even if no solar heat remains in storage. As a result of this, there are times when auxiliary heat supplies energy to storage to maintain storage at room air return temperature. This heat loss is not included in the heating load and was equal to 1.804 million Btu for the year.

TABLE 3.2.4-1

HEATING SUBSYSTEM PERFORMANCE

Month	Heating Parameters			Energy Consumed (Million Btu)			Measured Solar Fraction (Percent)
	Load (Million Btu)	Temperatures (°F)		Solar	Auxilary Thermal	Auxilary	
		Building	Outdoor				
Jan 80	5.93	69	47	1.27	5.01	5.01	21
Feb 79	8.40	74	45	1.20	8.20	8.20	15
Mar 80	4.54	73	54	2.02	2.69	2.69	45
Apr 79	0.10	75	67	0.10	0.00	0.00	100
May 79	0.00	76	72	0.00	0.00	0.00	0
Jun 79	0.00	73	79	0.00	0.00	0.00	0
Jul 79	0.00	77	81	0.00	0.00	0.00	0
Aug 79	0.00	75	80	0.00	0.00	0.00	0
Sep 79	0.00	75	74	0.00	0.00	0.00	0
Oct 79	0.68	74	65	0.56	0.13	0.13	82
Nov 78	1.91	72	59	1.29	0.61	0.61	69
Dec 78	6.45	72	47	2.52	4.17	4.17	39
Total	28.01	--	--	8.96	20.81	20.81	--
Average	2.33	74	64	0.75	1.73	1.73	32

Air leakage into the collector array during the storage to load mode of operation imposes a load on the system which is not included in the reported space heating load. Energy lost in this manner amounted to 1.855 million Btu for the year. These losses could be eliminated by fixing the leaks in the collector array.

The air conditioning system for this site is in parallel with the heating system. Both systems deliver air to two main supply ducts. The return air ducts are separate for each system. During check out of the solar heating system, it was discovered that when the air conditioning blower was operating, solar heat would leak into the building through the heating return air duct register. The leakage is caused by the air conditioning system which produces a positive pressure with respect to the dwelling and outside ambient in the two main supply ducts. This pressure differential induces a flow of air from the supply ducts into the solar system supply duct. Although the flow is impeded by motorized damper D2 and back draft damper D4 (see Figure 2.1), both dampers allow a small amount of air to pass through. Therefore, the cool air conditioned air forces hot air from storage into the building. This leakage was eliminated by inserting a cover plate in the return air register. The plate must be manually inserted when beginning the air conditioning season and removed when beginning the heating season.

4. OPERATING ENERGY

Operating energy for the IBM System 4 Solar Energy System is defined as the energy required to transport solar energy to the point of use. Total operating energy for this system consists of energy collection and storage subsystem operating energy and space heating subsystem operating energy. No operating energy is charged to the hot water subsystem. The collector blower operates to pass air through the heat exchanger (air to water) in the storage mode, but this energy is charged to energy collection and storage subsystem. The space heating blower operates to draw air from storage through the heat exchanger on its way to the load in the storage to load mode, but this energy is charged to the space heating subsystem. No operating energy is required to transfer water from the heat exchanger (air to water) to the preheat tank because the system utilizes the thermosyphoning principal and, therefore, no pump is required. Water flows from the preheat tank to the hot water tanks by city water supply water pressure which is not charged to the hot water subsystem. Measured monthly values for subsystem operating energy are presented in Table 4-1.

Energy collection and storage subsystem operating energy is the electrical energy required to operate the collector blower and control damper D1 and is measured by EP101. Space heating operating energy is the electrical energy required to operate the space heating blower and control damper D2 and is measured by EP400.

During the 12 month reporting period a total of 3.73 million Btu (1,096 kWh) of operating was consumed. The operating energy required to operate the space heating blower (2.21 million Btu) is not considered to be a solar peculiar operating energy, because this energy would be expended by the auxilary space heating system if the solar system were not involved. A total of 1.52 million Btu was allocated to the Energy Collector and Storage Subsystem (ECSS). Power consumption was twice as high during the summer months (June, July and August) when the system was in the summer mode. Operating energy consumption could be reduced during these months by not switching the system into the summer mode (See Section 3.2.3). Since a measured 12.63 million Btu of solar energy was delivered to the system loads during the reporting period, a total of 0.30 million Btu (88 kWh) of operating energy was required for each one million Btu of solar energy delivered to the system loads.

TABLE 4-1

OPERATING ENERGY

Month	ECSS Operating Energy (Million Btu)	Space Heating Operating Energy (Million Btu)	Total System Operating Energy (Million Btu)
Jan 80	0.06	0.46	0.52
Feb 79	0.08	0.79	0.87
Mar 80	0.11	0.32	0.43
Apr 79	0.09	0.01	0.10
May 79	0.08	0.00	0.08
Jun 79	0.23	0.00	0.23
Jul 79	0.19	0.00	0.19
Aug 79	0.25	0.00	0.25
Sep 79	0.13	0.00	0.13
Oct 79	0.11	0.05	0.16
Nov 78	0.09	0.12	0.21
Dec 78	0.10	0.46	0.56
Total	1.52	2.21	3.73
Average	0.13	0.18	0.31

5. ENERGY SAVINGS

Solar energy system savings are realized whenever energy provided by the solar energy system is used to meet system demands which would otherwise be met by auxiliary energy sources. The operating energy required to provide solar energy to the load subsystems is subtracted from the solar energy contribution, and the resulting energy savings are adjusted to reflect the coefficient of performance (COP) of the auxiliary source being supplanted by solar energy.

The IBM 4 System Solar Energy System uses electrical strip heat for auxiliary space heating and auxiliary energy for water heating is also provided by electricity. The electrical strip heat and the electrical hot water heating elements are considered to be 100 percent efficient.

Energy savings for the 12 month reporting period are presented by Table 5-1. During this time the system realized a net electrical energy savings of 8.05 million Btu, which is the sum of the solar energy supplied to the hot water subsystem and solar energy supplied to the space heating subsystem less the operating energy. This is equivalent to approximately 1.4 barrels of oil.

Energy savings would have been considerably higher for this system if the hot water load had been closer to the 130 gallon per day measured. Also, if the leaks in the collector array were fixed, the energy savings would be increased. The summer mode operation in the evening expended more energy to run the collector than the solar energy delivered to the preheat tank. It may be desirable not to use the summer mode of operation (See Section 3.2.3).

TABLE 5-1

ENERGY SAVINGS

Month	Electrical Energy Savings (Million Btu)			Solar Operating Energy (Million Btu)	Net Savings Electrical	
	Hot Water	Space Heating	Total		Million Btu	kwh
Jan 80	0.03	0.81	0.84	0.06	0.78	228.5
Feb 79	0.05	0.43	0.48	0.08	0.40	117.2
Mar 80	0.06	1.70	1.76	0.11	1.65	483.4
Apr 79	0. 39	0.10	0. 49	0.09	0.40	117.2
May 79	0.56	0.0	0.56	0.08	0.48	140.6
Jun 79	0.36	0.0	0.36	0.23	0.13	38.1
Jul 79	0.29	0.0	0.29	0.19	0.10	29.3
Aug 79	0.23	0.0	0.23	0.25	-0.02	-5.9
Sep 79	0.08	0.0	0.08	0.13	-0.05	-14.7
Oct 79	0.35	0.51	0.86	0.11	0.75	219.8
Nov 78	0.24	1.20	1.44	0.09	1.35	395.6
Dec 78	0. 11	2.07	2.18	0.10	2.08	609.4
Total	2. 75	6. 82	9. 57	1.52	8.05	2358.5
Average	0. 23	0. 57	0. 80	0.13	0. 67	196.5

6. MAINTENANCE

Several maintenance tasks were performed on this system during the monitoring period from October 1, 1978 until March 31, 1980 as follows:

October 1978 - The collector loop blower motor pulley failed at 8:30 AM on October 16. The pulley was a die cast item. Failure was apparently the result of the loosening of the set screw. Repair was accomplished the same day at 1:39 PM by replacing the damaged pulley with a new pulley. Water had been leaking into the space between the glazings for several months. Mineral deposits were beginning to build up on the inside of the glazings. The glazings were removed, cleaned and reinstalled on October 4.

November 1978 - The two glazing assemblies that were removed and cleaned in October were still exhibiting water condensation between glazings. The glazing assemblies were replaced with new ones.

December 1978 - A small water leak was found in the supply water line to the preheat tank. The leak was caused by a loose union. The leak was repaired on December 15 by removing pipe insulation, tightening the union and reinstalling the pipe insulation.

February 1979 - The potential freeze-up condition observed in January was eliminated by installing thermostatically controlled heater tapes on the water totalizer and preheat tank water lines. A leaky hot water faucet which began in January was repaired. A shattered outer glazing on one of the collectors was repaired by replacing the damaged glazing assembly with a new one. The cause of the breakage was unknown.

March 1979 - The top removable access panel of rock storage was adjusted for a tighter fit and the cracks formed between the cover and other storage mating surfaces were calked.

November 1979 - A clear plastic locking enclosure was installed over the thermostat at the site to eliminate occupant temperature control setting changes.

February 1980 - Leaky hot water faucets in both baths that were observed from preheat flow measurements were repaired.

7. SUMMARY AND CONCLUSIONS

During the 12 month reporting period, the measured daily average incident insolation in the plane of the collector array was 1,223 Btu/ft^2. This was 16 percent below the long-term daily average of 1,453 Btu/ft^2. There is no reason to suspect the accuracy of measured data. A possible explanation for the measured data to be lower than the long-term data is that the collector array is located near a dust access road to the dormitory. During dry periods, the array was covered with a coating of dust and presumably the pyranometer also was covered with dust. A coating of dust from time to time could reduce the measured insolation. The long-term annual heating degree day value for the adjacent city of Jackson, Mississippi is 2,300. The calculated heating degree day value from measured data during the reporting year was 2,530, which is 10% higher than the long-term value. The higher measured heating load together with the lower available insolation indicates that the measured performance should be lower than was predicted during the design phase. The solar energy system satisfied 32 percent of the total measured load (space heating and hot water). This was somewhat below the design value of 48 percent as described in Reference [10]. The reduction in overall performance is due to the variation between long-term and measured heating degree days and available insolation as described above. Also, leakage in the collector array as described in Sections 3.2.1 and 3.2.4, an open by-pass valve around the preheat tank and load related problems described in Section 3.2.3 are also responsible for measured performance reduction.

A total of 115.92 million Btu of incident solar energy was measured in the plane of the collector array during the reporting period. The system collected 25.77 million Btu of the available energy, which represents collector array efficiency of 23 percent. During periods when the collector array was active, a total of 78.52 million Btu was measured in the plane of the collector array. Therefore, the operational collector efficiency was 36 percent (based on an area adjustment of 1.1).

For the 12 month reporting period, a total of 22.37 million Btu of solar energy was delivered to rock storage. During the same period 14.12 million Btu was removed from storage. Of this amount, 0.75 million Btu was delivered

to the preheat tank, 4.46 million Btu was rejected during the summer mode of operation and the remainder was either delivered to the space heating system or lost in transport to the load. The effective storage heat loss coefficient was 16.5 Btu/Hr-°F, which is low and indicates a well insulated storage subsystem. The average temperature of storage was 122°F for the 12 month reporting period.

The hot water load for the reporting period was 3.48 million Btu. A total of 3.67 million Btu of solar energy and 4.92 million Btu of auxiliary energy were supplied to the subsystem, which represents a weighted hot water solar fraction of 33 percent. The average daily consumption of hot water was 20 gallons, delivered at an average temperature of 126°F. A total of 5.11 million Btu was lost from the hot water tank and preheat tank during the reporting period.

The space heating load for the reporting period was 28.01 million Btu. A total of 8.96 million Btu of solar energy and 20.81 Btu of auxiliary thermal energy were delivered to the space heating load to maintain the building average temperature at 74°F with an average outdoor temperature of 64°F. The 20.81 million Btu of auxiliary energy supplied to the space heating subsystem represents 6,097 kWh of electrical energy. The measured solar fraction was 32 percent.

A total of 1.52 million Btu, or 445 kWh, of electrical operating energy was reported to support the solar energy system during the 12 month reporting period. This does not include the electrical energy required to operate the fan in the auxiliary furnace. This fan would be required for operation of the space heating subsystem regardless of the presence of the solar energy system.

Gross electrical energy savings were 9.22 million Btu. However, when the 1.52 million Btu of electrical operating energy is taken into account, the net electrical energy savings were 7.70 million Btu, or 2,256 kWh. If a 30 percent efficiency is assumed for power generation and distribution, then the net electrical energy savings translate into a savings of 25.67 million Btu in generating station fuel requirements. This is equivalent to approximately 4.6 barrels of oil.

In general, the performance of the IBM Clinton solar energy system did not meet design expectations during the reporting period, since the overall design solar fraction was 48 percent and the measured value was 32 percent. Although the measured space heating solar fraction at 32 percent did agree favorably with the design space heating solar fraction at 35 percent, the hot water measured solar fraction at 33 percent did not agree favorably with the design hot water solar fraction of 63 percent. The reduced measured performance is due to a number of factors. In particular collector array air leakage, dust covered collectors, abnormal hot water demand and the preheat tank by-pass valve problem are main reasons for the lower performance. Detailed explanations are covered in Sections 3.2.1, 3.2.3 and 3.2.4.

The performance of the summer mode of operation was unsatisfactory. If the large temperature drop through the collector during the non-solar radiation period of operation (generally in the evening) is the result of the array leakage, the mode may prove to be profitable. If this is not the case, the summer mode should be deleted and the consequences of the collector stall condition in the summer accepted.

8. REFERENCES

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APPENDIX A

DEFINITION OF PERFORMANCE FACTORS AND SOLAR TERMS

APPENDIX A

DEFINITION OF PERFORMANCE FACTORS AND SOLAR TERMS

COLLECTOR ARRAY PERFORMANCE

The collector array performance is characterized by the amount of solar energy collected with respect to the energy available to be collected.

- INCIDENT SOLAR ENERGY (SEA) is the total insolation available on the gross collector array area. This is the area of the collector array energy-receiving aperture, including the framework which is an integral part of the collector structure.

- OPERATIONAL INCIDENT ENERGY (SEOP) is the amount of solar energy incident on the collector array during the time that the collector loop is active (attempting to collect energy).

- COLLECTED SOLAR ENERGY (SECA) is the thermal energy removed from the collector array by the energy transport medium.

- COLLECTOR ARRAY EFFICIENCY (CAREF) is the ratio of the energy collected to the total solar energy incident on the collector array. It should be emphasized that this efficiency factor is for the collector array, and available energy includes the energy incident on the array when the collector loop is inactive. This efficiency must not be confused with the more common collector efficiency figures which are determined from instantaneous test data obtained during steady state operation of a single collector unit. These efficiency figures are often provided by collector manufacturers or presented in technical journals to characterize the functional capability of a particular collector design. In general, the collector panel maximum efficiency factor will be significantly higher than the collector array efficiency reported here.

STORAGE PERFORMANCE

The storage performance is characterized by the relationships among the energy delivered to storage, removed from storage, and the subsequent change in the amount of stored energy.

- ENERGY TO STORAGE (STEI) is the amount of energy, both solar and auxiliary, delivered to the primary storage medium.

- ENERGY FROM STORAGE (STEO) is the amount of energy extracted by the load subsystems from the primary storage medium.

- CHANGE IN STORED ENERGY (STECH) is the difference in the estimated stored energy during the specified reporting period, as indicated by the relative temperature of the storage medium (either positive or negative value).

- STORAGE AVERAGE TEMPERATURE (TST) is the mass-weighted average temperature of the primary storage medium.

- STORAGE EFFICIENCY (STEFF) is the ratio of the sum of the energy removed from storage and the change in stored energy to the energy delivered to storage.

ENERGY COLLECTION AND STORAGE SUBSYSTEM

The Energy Collection and Storage Subsystem (ECSS) is composed of the collector array, the primary storage medium, the transport loops between these, and other components in the system design which are necessary to mechanize the collector and storage equipment.

- INCIDENT SOLAR ENERGY (SEA) is the total insolation available on the gross collector array area. This is the area of the collector array energy-receiving aperture, including the framework which is an integral part of the collector structure.

- AMBIENT TEMPERATURE (TA) is the average temperature of the outdoor environment at the site.

- ENERGY TO LOADS (SEL) is the total thermal energy transported from the ECSS to all load subsystems.

- AUXILIARY THERMAL ENERGY TO ECSS (CSAUX) is the total auxiliary supplied to the ECSS, including auxiliary energy added to the storage tank, heating devices on the collectors for freeze-protection, etc.

- ECSS OPERATING ENERGY (CSOPE) is the critical operating energy required to support the ECSS heat transfer loops.

HOT WATER SUBSYSTEM

The hot water subsystem is characterized by a complete accounting of the energy flow to and from the subsystem, as well as an accounting of internal energy. The energy into the subsystem is composed of electrical auxiliary thermal energy, and the operating energy for the subsystem. In addition, the solar energy supplied to the subsystem, along with solar fraction is tabulated. The load of the subsystem is tabulated and used to compute the estimated electrical savings of the subsystem. The load of the subsystem is further identified by tabulating the supply water temperature, and the outlet hot water temperature, and the total hot water consumption.

- HOT WATER LOAD (HWL) is the amount of energy required to heat the amount of hot water demanded at the site from the incoming temperature to the desired outlet temperature.

- SOLAR FRACTION OF LOAD (HWSFR) is the percentage of the load demand which is supported by solar energy.

- SOLAR ENERGY USED (HWSE) is the amount of solar energy supplied to the hot water subsystem.

- OPERATING ENERGY (HWOPE) is the amount of electrical energy required to support the subsystem, (e.g., fans, pumps, etc.) and which is not intended to affect directly the thermal state of the subsystem.

- AUXILIARY THERMAL USED (HWAT) is the amount of energy supplied to the major components of the subsystem in the form of thermal energy in a heat transfer fluid, or its equivalent. This term also includes the converted electrical and fossil fuel energy supplied to the subsystem.

- AUXILIARY ELECTRICAL FUEL (HWAE) is the amount of electrical energy supplied directly to the subsystem.

- ELECTRICAL ENERGY SAVINGS (HWSVE) is the estimated difference between the electrical energy requirements of an alternative conventional system (carrying the full load) and the actual electrical energy required by the subsystem.

- SUPPLY WATER TEMPERATURE (TSW) is the average inlet temperature of the water supplied to the subsystem.

- AVERAGE HOT WATER TEMPERATURE (THW) is the average temperature of the outlet water as it is supplied from the subsystem to the load.

- HOT WATER USED (HWCSM) is the volume of water used.

SPACE HEATING SUBSYSTEM

The space heating subsystem is characterized by performance factors accounting for the complete energy flow to and from the subsystem. The average building temperature and the average ambient temperature are tabulated to indicate the relative performance of the subsystem in satisfying the space heating load and in controlling the temperature of the conditioned space.

- SPACE HEATING LOAD (HL) is the sensible energy added to the air in the building.

- SOLAR FRACTION OF LOAD (HSFR) is the fraction of the sensible energy added to the air in the building derived from the solar energy system.

- SOLAR ENERGY USED (HSE) is the amount of solar energy supplied to the space heating subsystem.

- OPERATING ENERGY (HOPE) is the amount of electrical energy required to support the subsystem, (e.g., fans, pumps, etc.) and which is not intended to affect directly the thermal state of the subsystem.

- AUXILIARY THERMAL USED (HAT) is the amount of energy supplied to the major components of the subsystem in the form of thermal energy in a heat transfer fluid or its equivalent. This term also includes the converted electrical and fossil fuel energy supplied to the subsystem.

- <u>ELECTRICAL ENERGY SAVINGS</u> (HSVE) is the cost of the operating energy (HOPE) required to support the solar energy portion of the space heating subsystem.

- <u>BUILDING TEMPERATURE</u> (TB) is the average heated space dry bulb temperature.

- <u>AMBIENT TEMPERATURE</u> (TA) is the average ambient dry bulb temperature at the site.

ENVIRONMENTAL SUMMARY

The environmental summary is a collection of the weather data which is generally instrumented at each site in the Development Program. It is tabulated in this report for two purposes (1) as a measure of the conditions prevalent during the operation of the system at the site, and (2) as a historical record of weather data for the vicinity of the site.

- TOTAL INSOLATION (SE) is the accumulated total solar energy incident upon the gross collector array measured at the site.

- AMBIENT TEMPERATURE (TA) is the average temperature of the environment at the site.

- DAYTIME AMBIENT TEMPERATURE (TDA is the temperature during the period from three hours before solar noon to three hours after solar noon.

APPENDIX B

SOLAR ENERGY SYSTEM PERFORMANCE EQUATIONS
IBM 4 CLINTON

APPENDIX B

SOLAR ENERGY SYSTEM PERFORMANCE EQUATIONS FOR IBM 4 CLINTON

I. INTRODUCTION

Solar energy system performance is evaluated by performing energy balance calculations on the system and its major subsystems. These calculations are based on physical measurement data taken from each subsystem every 320 seconds. This data is then numerically combined to determine the hourly, daily, and monthly performance of the system. This appendix describes the general computational methods and the specific energy balance equations used for this evaluation.

Data samples from the system measurements are numerically integrated to provide discrete approximations of the continuous functions which characterize the system's dynamic behavior. This numerical integration is performed by summation of the product of the measured rate of the appropriate performance parameters and the sampling interval over the total time period of interest.

There are several general forms of numerical integration equations which are applied to each site. Examples of these general forms are as follows: The total solar energy available to the collector array is given by

$$\text{SOLAR ENERGY AVAILABLE} = (1/60)\ \Sigma\ [\text{I001} \times \text{AREA}] \times \Delta\tau$$

where I001 is the solar radiation measurement provided by the pyranometer in Btu/ft^2-hr, AREA is the area of the collector array in square feet, $\Delta\tau$ is the sampling interval in minutes, and the factor (1/60) is included to correct the solar radiation "rate" to the proper units of time.

Similarly, the energy flow within a system is given typically by

$$\text{COLLECTED SOLAR ENERGY} = \Sigma\ [\text{M100} \times \Delta H] \times \Delta\tau$$

where M100 is the mass flow rate of the heat transfer fluid in lb_m/min and ΔH is the enthalpy change, in Btu/lb_m, of the fluid as it passes through the heat exchanging component.

For a liquid system ΔH is generally given by

$$\Delta H = \overline{C}_p\ \Delta T$$

where $\overline{C}_p$ is the average specific heat, in Btu/(lb_m-°F), of the heat transfer fluid and ΔT, in °F, is the temperature differential across the heat exchanging component.

For an air system ΔH is generally given by

$$\Delta H = H_a(T_{out}) - H_a(T_{in})$$

where $H_a(T)$ is the enthalpy, in Btu/lb_m, of the transport air evaluated at the inlet and outlet temperatures of the heat exchanging component.

$H_a(T)$ can have various forms, depending on whether or not the humidity ratio of the transport air remains constant as it passes through the heat exchanging component.

For electrical power, a general example is

$$\text{ECSS OPERATING ENERGY} = (3413/60)\ \Sigma\ [\text{EP100}] \times \Delta\tau$$

where EP100 is the measured power required by electrical equipment in kilowatts and the two factors (1/60) and 3413 correct the data to Btu/min.

These equations are comparable to those specified in "Thermal Data Requirements and Performance Evaluation Procedures for the National Solar Heating and Cooling Demonstration Program." This document, given in the list of references, was prepared by an inter-agency committee of the government, and presents guidelines for thermal performance evaluation.

Performance factors are computed for each hour of the day. Each numerical integration process, therefore, is performed over a period of one hour. Since long-term performance data is desired, it is necessary to build these hourly performance factors to daily values. This is accomplished, for energy parameters, by summing the 24 hourly values. For temperatures, the hourly values are averaged. Certain special factors, such as efficiencies, require appropriate handling to properly weight each hourly sample for the daily value computation. Similar procedures are required to convert daily values to monthly values.

II. PERFORMANCE EQUATIONS

The performance equations for IBM 4 Clinton used for the data evaluation of this report are contained in the following pages and have been included for technical reference and information.

EQUATIONS USED IN MONTHLY PERFORMANCE ASSESSMENT

NOTE: MEASUREMENT NUMBERS REFERENCE SYSTEM SCHEMATIC FIGURE 2-1

AVERAGE AMBIENT TEMPERATURE (°F)

$TA = (1/60) \times \Sigma\ T001 \times \Delta\tau$

AVERAGE BUILDING TEMPERATURE (°F)

$TB = (1/60) \times \Sigma\ T600 \times \Delta\tau$

DAYTIME AVERAGE AMBIENT TEMPERATURE (°F)

$TDA = (1/360) \times \Sigma\ T001 \times \Delta\tau$

FOR $\pm$ 3 HOURS FROM SOLAR NOON

INCIDENT SOLAR ENERGY PER SQUARE FOOT (BTU/FT^2)

$SE = (1/60) \times \Sigma\ I001 \times \Delta\tau$

OPERATIONAL INCIDENT SOLAR ENERGY (BTU)

$SEOP = (1/60) \times \Sigma\ [I001 \times CLAREA] \times \Delta\tau$

WHEN THE COLLECTOR LOOP IS ACTIVE

HUMIDITY RATIO FUNCTION (BTU/LBM-°F)

$HRF = 0.24 + 0.444 \times HR$

WHERE 0.24 IS THE SPECIFIC HEAT AND HR IS THE HUMIDITY RATIO OF THE TRANSPORT AIR. THIS FUNCTION IS USED WHENEVER THE HUMIDITY RATIO WILL REMAIN CONSTANT AS THE TRANSPORT AIR FLOWS THROUGH A HEAT EXCHANGING DEVICE

SOLAR ENERGY COLLECTED BY THE ARRAY (BTU)

$SECA = \Sigma\ [M100 \times HRF \times (T150 - T100)] \times \Delta\tau$

ENERGY REJECTED BY COLLECTOR ARRAY (BTU)

$SECA1 = \Sigma\ [M100 \times HRF \times (T101 - T100)] \times \Delta\tau$

$CSRJE = -SECA1$

ENTHALPY FUNCTION FOR WATER (BTU/LBM)

$$HWD(T_2, T_1) = \int_{T_1}^{T_2} C_p(T)dT$$

THIS FUNCTION COMPUTES THE ENTHALPY CHANGE OF WATER AS IT PASSES THROUGH A HEAT EXCHANGING DEVICE.

SOLAR ENERGY TO STORAGE (BTU)

$$STEI1 = \Sigma\ [M100 \times HRF \times (T106 - T100)] \times \Delta\tau$$

AUXILIARY ENERGY TO STORAGE (BTU)

$$CSAUX = \Sigma\ [M400 - M100) \times HRF \times (T403 - T106)] \times \Delta\tau$$

TOTAL ENERGY TO STORAGE (BTU)

$$STEI = STEI1 + CSAUX$$

ENERGY REMOVE FROM STORAGE (BTU)

WHEN GOING TO SPACE HEATING LOAD

$$STEO = \Sigma\ [(M400 - M100) \times HRF \times (T106 - T403)] \times \Delta\tau$$

WHEN GOING TO COLLECTOR (SUMMER MODE)

$$STEO = \Sigma\ [(M100 \times HRF \times (T100 - T106)] \times \Delta\tau$$

$$STEI2 = \Sigma\ [(M100 \times HRF \times (T106 - T100)] \times \Delta\tau$$

AVERAGE TEMPERATURE OF STORAGE (°F)

$$TST = (1/60) \times \Sigma\ [(T200 + T201 + T\ 202)\ /3] \times \Delta\tau$$

SOLAR ENERGY FROM COLLECTOR ARRAY TO SPACE HEATING LOAD (BTU)

$$CSE01 = \Sigma\ [M100 \times HRF \times (T101 - T100)] \times \Delta\tau$$

ECSS OPERATING ENERGY (COLLECTOR BLOWER) (BTU)

$$CSOPE = 56.8833 \times \Sigma\ (EP101) \times \Delta\tau$$

SOLAR ENERGY TO PREHEAT TANK (BTU)

WHEN COMING FROM COLLECTORS

$$PHTSE1 = \Sigma\ [M100 \times HRF \times (T105 - T106)] \times \Delta\tau$$

WHEN COMING FROM STORAGE

$$PHTSE2 = \Sigma\ [M400 \times HRF \times (T106 - T105)] \times \Delta\tau$$

$$PHTSE3 = \Sigma\ [(M400 - M100) \times HRF \times (T106 - T105)] \times \Delta\tau$$

WHEN IN SUMMER MODE

$$PHTSE4 = PHTSE1$$

AUXILIARY SPACE HEAT TO PREHEAT TANK (BTU)

$$PHTCSAUX2 = \Sigma\ [M400 * HRF * (T106 - T105)] \times \Delta\tau$$

$$PHTCSAUX3 = \Sigma\ [(M400 - M100) * HRF * (T106 - T105)] \times \Delta\tau$$

SOLAR ENERGY FROM PREHEAT TANK ENERGY TO HOT WATER TANKS (BTU)

$$HWSE1 = \Sigma\ [M301 \times HWD\ (T300, T301)] \times \Delta\tau$$

HOT WATER SUBSYSTEM AUXILIARY ELECTRICAL FUEL ENERGY (BTU)

$$HWAE = 56.8833 \times \Sigma\ (EP300 + EP301) \times \Delta\tau$$

HOT WATER CONSUMED (GALLONS)

$$HWCSM = \Sigma\ WD300 \times \Delta\tau$$

HOT WATER LOAD (BTU)

$HWL = \Sigma\,[M302 \times HWD\,(T309,T301) + (M301 - M302) * HWD\,(T304,T301)] \times \Delta\tau$

HOT WATER AUXILIARY THERMAL ENERGY (BTU)

$HWAT = HWAE$

SUPPLY WATER TEMPERATURE (°F)

$TSW = T301$

HOT WATER TEMPERATURE (°F)

$THW = (T304 + T309)\,/2$

BOTH TSW AND THW ARE COMPUTED ONLY WHEN FLOW EXISTS IN THE SUBSYSTEM, OTHERWISE THEY ARE SET EQUAL TO THE VALUES OBTAINED DURING THE PREVIOUS FLOW PERIOD.

SPACE HEATING OPERATING ENERGY (BTU)

$HOPE = 56.8833 \times \Sigma\,(EP400) \times \Delta\tau$

SPACE HEATING SUBSYSTEM ELECTRICAL FUEL ENERGY (BTU)

$HAE = 56.8833 \times \Sigma\,(EP401) \times \Delta\tau$

SPACE HEATING SUBSYSTEM AUXILIARY THERMAL ENERGY (BTU)

$HAT = HAE$

SPACE HEATING SUBSYSTEM ELECTRICAL ENERGY SAVINGS (BTU)

$HSVE = HSE - HOPE$

SPACE HEATING LOAD (BTU)

$HL = HSE + HAT - CSAUX$

SPACE HEATING SUBSYSTEM SOLAR FRACTION (PERCENT)

$HSFR = 100 \times HSE/HL$

INCIDENT SOLAR ENERGY ON COLLECTOR ARRAY (BTU)

$SEA = CLAREA \times SE$

COLLECTED SOLAR ENERGY (BTU/FT^2)

$SEC = SECA/CLAREA$

COLLECTOR ARRAY EFFICIENCY

$CAREF = SECA/SEA$

CHANGE IN STORED ENERGY (BTU)

$STECH = STECH1 - STECH1_p$

WHERE THE SUBSCRIPT $_p$ REFERS TO A PRIOR REFERENCE VALUE

STORAGE EFFICIENCY

$STEFF = (STECH + STEO)/STEI$

ECSS SOLAR CONVERSION EFFICIENCY

$CSCEF = SEL/SEA$

HOT WATER ELECTRICAL SAVINGS

HWSVE = HWSE1

APPARENT SOLAR ENERGY TO HOT WATER SUBSYSTEM (BTU)

HWSEAUX = PHTSE

ACTUAL SOLAR ENERGY TO HOT WATER SUBSYSTEM (BTU)

HWSE = HWSEAUX - HWSEAUX x CSAUX x STEFF/(HSEAUX + HWSEAUX)

APPARENT SOLAR ENERGY TO SPACE HEATING LOAD (BTU)

HSEAUX = STEO + STEI2 + CSEO1 - PHTSE2 - PHTSE3

ACTUAL SOLAR ENERGY TO SPACE HEATING LOAD (BTU)

HSE = HSEAUX - HSEAUX x CSAUX x STEFF/(HSEAUX + HWSEAUX)

ENERGY DELIVERED FROM ECSS TO LOAD SUBSYSTEMS (BTU)

CSEO = HSE + HWSE + CSAUX x STEFF

HOT WATER SOLAR FRACTION (PERCENT)

HWSFR = 100 x HWTKSE/(HWTKSE + HWTKAUX)

WHERE HWTKSE AND HWTKAUX REPRESENT THE CURRENT SOLAR AND AUXILIARY ENERGY CONTENT OF THE HOT WATER TANK

SOLAR ENERGY TO LOAD SUBSYSTEMS (BTU)

SEL = HWSE1 + HSE

SYSTEM LOAD (BTU)

SYSL = HL + HWL

SOLAR FRACTION OF SYSTEM LOAD (PERCENT)

SFR = (HL x HSFR + HWL x HWSFR)/SYSL

SYSTEM OPERATING ENERGY (BTU)

SYSOPE = HOPE + SCOPE

AUXILIARY THERMAL ENERGY TO LOADS (BTU)

AXT = HWAT + HAT

AUXILIARY ELECTRICAL ENERGY TO LOADS (BTU)

AXE = HWAE + HAE

TOTAL ELECTRICAL ENERGY SAVINGS (BTU)

TSVE = HWSVE + HSVE - CSOPE

TOTAL ENERGY CONSUMED (BTU)

TECSM = SYSOPE + AXE + SECA

SYSTEM PERFORMANCE FACTOR

SYSPF = SYSL/(AXF + (AXE + SYSOPE) x 3.33)

APPENDIX C

LONG-TERM AVERAGE WEATHER CONDITIONS

APPENDIX C

LONG-TERM AVERAGE WEATHER CONDITIONS

The environmental estimates given in this appendix provide a point of reference for evaluation of weather conditions as reported in the Monthly Performance Assessments and Solar Energy System Performance Evaluations issued by the National Solar Data Program. As such, the information presented can be useful in prediction of long-term system performance.

Environmental estimates for this site include the following monthly averages: extraterrestrial insolation, insolation on a horizontal plane at the site, insolation in the tilt plane of the collection surface, ambient temperature, heating degree-days, and cooling degree-days. Estimation procedures and data sources are detailed in the following paragraphs.

The preferred source of long-term temperature and insolation data is "Input Data for Solar Systems" (IDSS) [1] since this has been recognized as the solar standard. The IDSS data are used whenever possible in these environmental estimates for both insolation and temperature related sources; however, a secondary source used for insolation data is the Climatic Atlas of the United States [2], and for temperature related data, the secondary source is "Local Climatological Data" [3].

Since the available long-term insolation data are only given for a horizontal surface, solar collection subsystem orientation information is used in an algorithm [4] to calculate the insolation expected in the tilt plane of the collector. This calculation is made using a ground reflectance of 0.2.

No listing for Togus, Maine is given in any of the preferred primary data sources. It is therefore necessary to interpolate among data given by nearby weather stations to derive an estimate. For insolation estimates, IDSS data from Bangor, Maine and Portland, Maine are used in the proportions of 0.4595 to 0.5405, respectively. For temperature related estimates, IDSS data from Caribou, Maine and Portland, Maine are proportioned 0.2099 and 0.7901.

SITE: IBM CLINTON 87. LOCATION: JACKSON MS

ANALYST: D. LINTON FORIVE NO.: 76.

COLLECTOR TILT: 45.00 (DEGREES) COLLECTOR AZIMUTH: 0.0 (DEGREES)

LATITUDE: 32.32 (DEGREES) RUN DATE: 08/30/79

MONTH	HOBAR	HBAR	KBAR	RBAR	SBAR	HDD	CDD	TBAR
JAN	1734.	752.	0.43373	1.494	1124.	569	14	47.
FEB	2160.	1025.	0.47464	1.318	1351.	442	17	59.
MAR	2677.	1368.	0.51096	1.118	1529.	313	37	56.
APR	3174.	1707.	0.53785	0.933	1592.	74	95	66.
MAY	3490.	1939.	0.55566	0.812	1575.	6	245	73.
JUN	3606.	2024.	0.56129	0.762	1543.	0	432	79.
JUL	3540.	1910.	0.53953	0.786	1501.	0	518	82.
AUG	3287.	1781.	0.54172	0.879	1565.	0	502	81.
SEP	2850.	1508.	0.52905	1.041	1570.	0	330	76.
OCT	2307.	1272.	0.55147	1.230	1629.	91	116	66.
NOV	1831.	903.	0.49330	1.489	1345.	301	10	55.
DEC	1613.	708.	0.43859	1.568	1110.	504	5	49.

LEGEND:

HOBAR ==> MONTHLY AVERAGE DAILY EXTRATERRESTRIAL RADIATION (IDEAL) IN BTU/DAY-FT2.

HBAR ==> MONTHLY AVERAGE DAILY RADIATION (ACTUAL) IN BTU/DAY-FT2.

KBAR ==> RATIO OF HBAR TO HOBAR.

RBAR ==> RATIO OF MONTHLY AVERAGE DAILY RADIATION ON TILTED SURFACE TO THAT ON A HORIZONTAL SURFACE FOR EACH MONTH (I.E., MULTIPLIER OBTAINED BY TILTING).

SBAR ==> MONTHLY AVERAGE DAILY RADIATION ON A TILTED SURFACE (I.E., RBAR * HBAR) IN BTU/DAY-FT2.

HDD ==> NUMBER OF HEATING DEGREE DAYS PER MONTH.

CDD ==> NUMBER OF COOLING DEGREE DAYS PER MONTH.

TBAR ==> AVERAGE AMBIENT TEMPERATURE IN DEGREES FAHRENHEIT.

REFERENCES

[1] Cinquemani, V., et al. "Input Data for Solar Systems." Prepared for the U.S. Department of Energy by the National Climatic Center, Asheville, NC, 1978.

[2] United States Department of Commerce, Climatic Atlas of the United States, Environmental Data Service, Reprinted by the National Oceanic and Atmospheric Administration, Washington, DC, 1977.

[3] United States Department of Commerce, "Local Climatological Data," Environmental Data Service, National Oceanic and Atmospheric Administration, Asheville, NC, 1977.

[4] Klein, S. A., "Calcula'ion of Monthly Average Insolation on Tilted Surfaces," Joint Confe:ence 1976 of the International Solar Energy Society and the Solar Energy Society of Canada, Inc., Winnipeg, August 15-20, 1976.

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